NBS TECHNICAL NOTE 1113-2

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Highway Noise Criteria Study: Outdoor/Indoor Noise Isolation

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Issued August 1980

National Bureau of Standards Technical Note 1113-2
Nat. Bur. Stand. (U.S.), Tech. Note 1113-2, 180 pages (Aug. 1980)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1980

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Price $6.
(Add 25 percent for other than U.S. mailing)

Abstract

This report documents a series of measurements of the outdoor-to-indoor noise isolation provided by nine houses in the Washington, DC, area. These measurements were carried out as part of a large research program developed to identify and quantify the important physical parameters which affect human response to time-varying traffic noise and to investigate various procedures for rating such noise so as to enable reliable predictions of subjective response to the noise. While a small truck was driven past each test house, simultaneous recordings were made of the sound level at three outdoor microphones and at four indoor microphones (three of which were positioned at representative listener positions). These recordings were analyzed to yield one-third octave band sound levels as functions of time and from these levels outdoor-to-indoor level differences were computed. Analyses are given of the influence of different experimental variables. It is found that microphone placement, both indoors and outdoors, is the major source of measurement uncertainty. The data from this study are in good agreement with sound isolation data reported in the literature for houses in colder climates.

Key words: Acoustics; building acoustics; environmental pollution; noise control; noise isolation; sound.

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1. Introduction

The measurements documented in this report were obtained as part of a larger research program [1][1] having the following main objectives:

- to identify and quantify important physical parameters which affect human response to time-varying traffic noise associated with varying densities of both free-flowing highway traffic and stop-and-go traffic;

- to investigate and compare various measures and computational procedures for rating time-varying traffic noise and to investigate which method (or methods) best predicts the subjective response of people to the noise from various types of traffic situations;

- to develop, if necessary, improved procedures for rating time-varying traffic noise in terms of measurable parameters of the noise; and

- to formulate procedures by which the most useful of the above rating procedures may be related to other commonly used environmental noise descriptors.

These objectives are to be achieved mainly through a series of psychoacoustic experiments designed to measure human response to a variety of traffic noises. Stimuli for these experiments will be selected from a library of audio recordings of traffic noise which was also obtained as part of the overall program [2]. Since people are often exposed to traffic noise while indoors, the effects of time-varying traffic noise on human response should be studied under conditions of listeners located both indoors and outdoors. To simulate indoor listening conditions, the traffic noises recorded in this program will be modified on playback, using electrical filters, so as to sound approximately as they would when transmitted from outside to inside a building.

In order to develop a filter which will simulate transmission of traffic noise from outdoors to indoors, a series of measurements was conducted to determine the sound isolation provided by residential building shells. For this purpose, a measure of sound isolation termed Noise Intrusion Reduction (NIR) was used (see Section 2). Values of NIR were determined using analog tape recordings of sound pressure taken simultaneously indoors and outdoors at each of nine single-family dwellings in the greater metropolitan Washington, D.C., area. These analog recordings were subsequently reduced to indoor and outdoor 1/3-octave band sound pressure levels. These levels were then used to compute values of NIR. The NIR data obtained in the current study are compared to outdoor-to-indoor sound isolation data reported in the literature.

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[1] Figures in square brackets indicate the literature references in Section 7 of this report.

The data obtained in this study were used to examine general problems that may arise in the measurement of building sound isolation. In particular, sources of error in measuring exterior and interior sound pressure levels, for the purpose of determining building sound isolation, are examined.

The remainder of this report is divided into six sections. A discussion of measures of building sound isolation is presented in Section 2. A description of measurement procedures, sites, and data reduction techniques used in the current study is provided in Section 3. The resulting NIR data are presented in Section 4. A discussion of the NIR values obtained in the current study is presented in Section 5. Implications of the results of the current study to measures of building sound isolation are discussed in Section 6. Section 7 contains the literature references used throughout the report. Appendices A through E include floor plans of houses included in the measurements, the complete set of NIR values, and the electronic design of two outdoor-to-indoor sound transmission filters.

2. Measures of Building Sound Isolation

The outdoor-to-indoor sound isolation of a building shell is a measure of the degree of lack of acoustical connection between the outdoor and indoor environments [3]. This sound isolation includes the attenuation of sound in traveling from the source to the outside of the building, the sound insulation provided by the elements of the building shell, and any attenuation occurring as the sound propagates inside the building to the point of reception. Building sound insulation is typically quantified by a measure of the sound transmission loss of the building facade or facade elements.[1]

Several definitions of building sound isolation and insulation are in use by different standards organizations. The International Organization for Standardization (ISO) has issued a standard test procedure [4] for determining the field sound transmission loss of building facades and facade elements. The American Society for Testing and Materials (ASTM) is developing a similar standard [5]. ASTM [3] defines outside-to-inside level reduction[2] for an enclosure as a measure of the sound isolation properties of the building facade and the receiving room. For the determination of both facade sound transmission loss and outside-to-inside level reduction, microphone locations within the test room are chosen to yield a spatial average (on a mean-square pressure basis) sound pressure level over the volume of the room.

For the purposes of the current study, the reduction of outdoor noise intrusion into the building was determined as it would be experienced by listeners located indoors. Thus, microphone positions corresponding to probable listener positions within the room were used rather than receiver positions which might be used to determine the spatial average mean-square sound pressure level over the volume of the room. Accordingly, a sound isolation metric dubbed "Noise Intrusion Reduction" (NIR) has been defined.

2.1 Definitions

A measure of facade sound transmission loss is defined both by ASTM and ISO in similar test procedures for the determination of building facade sound insulation. In the ASTM proposed standard [5], the sound transmission loss of the facade element, when traffic noise (or similar natural source) is incident on the facade, is defined by:

$$TL = L_1 - \langle L_2 \rangle + 10 \log_{10} (S/A), \qquad (1)$$

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[1]Sound transmission loss is defined as the ratio, expressed on the decibel scale, of the airborne sound power incident on the partition to the sound power transmitted by the partition and radiated on the other side [3].

[2]Level reduction is defined as the decrease in sound pressure level, measured at the location of the receiver, when a barrier or other sound-reducing element is placed between the source and the receiver [3].

where L_1 is the outdoor time-averaged sound pressure level, $\langle L_2 \rangle$ is the time-averaged sound pressure level spatially averaged over the volume of the receiving room, S is the area of the facade element, and A is the absorption of the room as a function of frequency. Equation (1) corresponds to sound incident over a large range of angles rather than from a single direction. In the ISO standard [4], a "sound reduction index" (R_{tr}) is similarly defined. Note that both the ISO and ASTM procedures require a measure of the spatially averaged mean-square sound pressure over the volume of the receiving room.

As discussed above, outside-to-inside sound level reduction has been defined by ASTM as a particular measure of building sound isolation. Level reduction is defined by ASTM [6] by the expression:

$$LR = L_1 - \langle L_2 \rangle , \qquad (2)$$

where L_1 and $\langle L_2 \rangle$ are the same quantities as defined above. Equation (2) has no terms to account for test partition size or receiving room absorption. Such terms are omitted in LR as this quantity is not intended to be a measure of the sound insulation of the facade, but rather is a measure of overall sound isolation from outdoors to indoors.

In order to assess the reduction of the environmental noise intrusion as would be typically experienced by occupants of a building, a measure of sound isolation is required which combines the effects of facade sound transmission loss and the attenuation provided within the room. Further, to assess the reduction of noise intrusion as experienced by occupants in the receiving room, it is necessary to examine sound isolation at probable locations of room occupants rather than at positions chosen to yield the spatial average sound pressure level in the room. For these two reasons, the expressions defined in Eqs. (1) and (2) were not considered to be appropriate for the purposes of the current study. Therefore, the Noise Intrusion Reduction (NIR) was defined as a measure of building sound isolation corresponding to probable occupant locations within the test room. Noise Intrusion Reduction is defined by the expression:

$$NIR = L_1 - L_{LP} , \qquad (3)$$

where L_{LP} is the sound pressure level at a listener position, or averaged over a number of listener positions, in the receiving room. As in the expression for outdoor-to-indoor level reduction, Eq. (2), no terms are presented in Eq. (3) to account for test partition size or receiving room absorption. Omission of such terms is consistent with a measure of building sound isolation which combines the overall isolation due to the facade insulation and the attenuation within the receiving room.

A number of specific measures of building sound isolation have been reported in the literature [7-19]. Generally, these measure are defined so as to correspond to Eqs. (1), (2), or (3).

2.2 Measurement Considerations for Outdoor and Indoor Sound Fields

Common to the determinations of all of the building sound isolation quantities is the quantification of the exterior and interior sound fields. Some of the problems and uncertainties in both of these sound pressure level measurements are mentioned below. Additionally, the procedures used to measure exterior and interior sound pressure levels specified in the existing proposed standards and in the literature are presented. (Some of the measurement problems associated with such measurements have been examined by Mulholland [20] and by Lewis [21].)

2.2.1 Measurement of Outdoor Sound Pressure Levels

2.2.1.1 Microphone Placement

Ideally, in order to determine building sound isolation, it would be desirable to measure the outdoor sound pressure level at the building site with the building not present. However, as this is not typically possible, the measurement of the outdoor sound field must be made in the presence of reflecting surfaces introduced by the building, in addition to the existing ground plane. The presence of building surfaces complicates the measurement of the outdoor sound field because the reflected sound interferes with the direct sound from the noise source, thereby creating spatial and temporal variations in the sound field relative to those that would exist in the absence of the building. Characterization of the influence of the reflected sound is complicated due to the finite (and possibly complex) impedance of the building surface and ground cover and to irregularities in the surface created by facade structures such as window and door recesses.

For measurement of outdoor sound pressure levels in conjunction with the ISO [4] and the proposed ASTM [5] standards, it is stated that the microphone is to be placed 2 m from the building surface. As an alternative, in the ISO standard a microphone distance of less than 2 cm may be used.

In the literature several additional microphone positions relative to the building facade have been used to measure outdoor sound pressure levels. In a number of studies, a microphone distance of 1 m has been used. In one study, the microphone was placed 4.5 cm from the building surface, corresponding to the radius of a microphone windscreen [7]. Many of the reported studies do not include information on microphone placement or supply vague information such as "away" from or "several feet" from the building.

As an alternative to measuring the existing sound field outside a building with a microphone placed in the vicinity of the building surface, both the ISO and ASTM procedures allow the use of a controlled loudspeaker noise source to infer the exterior sound pressure level. Using this technique,

the sound level produced at the test facade by a loudspeaker is inferred from an earlier measurement of the level produced by the loudspeaker. This is determined by measuring the level produced at a corresponding location relative to the loudspeaker when the loudspeaker is installed in an environment similar to that in which the test is to be made, but with no vertical building surface present. The electrical input corresponding to the measured sound level is then set and is maintained during the actual facade test. In this manner, the level of the incident sound is known, uncomplicated by reflection from the test facade.

2.2.1.2 Position of Exterior Sources of Noise

In addition to the positioning of the microphone relative to the exterior building surface, the angle of incidence of the exterior sound will affect measured values of sound isolation because of the angular dependence of the sound transmission loss of facade elements. For infinitely large panels, the dependence of sound transmission loss on incidence angle can be demonstrated theoretically [22,23]. Although this model may not be representative of actual building facades, the angular dependence of sound transmission loss for windows has been demonstrated both theoretically and experimentally [23-25]. Because of such angular dependencies, the position of the exterior source of noise relative to the test facade is of importance in characterizing building sound isolation properties.

The position of the exterior source of noise is specified in a similar manner in both the ISO and proposed ASTM standards for the measurement of facade sound transmission loss. If the building facade to be assessed is exposed to traffic noise, both of the standards recommend using the time-averaged sound pressure level measured 2 m from the building facade as the exterior level in Eq. (2). Typically, this measurement provides some averaging over incident angle for the exterior sounds as well as providing some characterization of the sound transmission loss of the facade for the environmental noise sources to which it is normally exposed. If a controlled loudspeaker noise source is used to determine sound insulation, both test methods require an incidence angle of 45° from normal with other angles being included as options.

The position of the noise source relative to the test structure is often dictated by the intent of the outdoor-to-indoor sound isolation measurement. In the literature, numerous studies have used aircraft overflights as the noise source. This was done because the intent was to determine the effectiveness of the test structure in reducing aircraft noise. In most of these studies, the position of the source relative to the structure is not well known. In some cases, there is no one defined source position. This occurs because reported noise reduction values correspond to the difference between the maximum exterior level and the maximum interior level regardless of when either occurred during the overflight [9,17,19]. In one recent study, the intent of the measurement was to assess the performance of dwellings

in reducing noise from electrical transmission lines [15]. Due to the (spatially) linear nature of the source in this case, loudspeaker noise sources were placed outside the building in a line parallel to the building surface.

The position of the exterior noise source is also important in sound isolation determinations due to multiple sound transmission paths in the structure. For most surface transportation noise sources, sound is transmitted primarily through windows and doors and to a lesser extent through the wall structure itself [26]. However, if the noise source is elevated, other transmission paths, including roof-ceiling systems and chimney flues, may become significant [11,26]. The occurrence of such multiple transmission paths further complicates the measurement of the exterior sound field when the multiple transmission paths are spatially distributed over the test structure. In this case, microphone placement should be such as to characterize adequately the sound incident on each element contributing to the sound transmission.

2.2.2 Measurement of Indoor Sound Pressure Levels

The measurement procedures used to characterize the indoor sound field are dependent on the type of sound isolation measurement to be made. If the sound transmission loss of the facade or the outdoor-to-indoor level reduction as defined by Eq. (2) is to be determined, an estimation of the spatially averaged (on a mean-square pressure basis) sound pressure level within the receiving room is necessary. If the reduction of outdoor environmental noise exposure produced within a room by the building shell is to be determined for occupants of that room, an estimation of sound levels occurring at probable listener locations within the room is necessary. For either of these purposes, significant variations in sound pressure levels measured at different discrete points within the receiving room may occur.

Spatial variation of measured indoor sound pressure levels, particularly for living spaces, can occur for a variety of reasons. At low frequencies, the principal reason is wave phenomena within the enclosed space of the receiving room, resulting in local variations in sound pressure level [22]. Spatial variations can occur due to the finite size of the radiating surfaces (e.g. windows and walls) within the room, multiple transmission paths through the building shells, the presence of furnishings within the receiving room, and the position and temporal characteristics of the exterior sound source. For many living spaces, spatial variations are further complicated by the typical sound absorptive nature of such spaces. Furnishings (e.g., chairs, sofas, carpeting, drapes) within the receiving room can act both to increase spatial variation by providing localized absorption and shielding of sound and to decrease spatial variation by providing localized scattering of sound and by increasing modal bandwidths for the room acoustic resonances.

Procedures for the determination of the spatially averaged sound pressure level within the receiving room are not explicitly provided in the ISO and the proposed ASTM standards. In the ISO standard [4], the location and number of interior measurement points to be used to determine the average interior mean-squared pressure are not specified. However, in an example cited in the standard, six randomly distributed microphone positions are used with no position nearer than 0.5 m from a room boundary or nearer than 1 m from the exterior wall under test. Similarly, in the proposed ASTM standard, measurement points are not specified other than the requirement that none be within 1 m of the exterior wall [5]. The ASTM proposed procedure allows the use of a single microphone position at the approximate center of the room if preliminary measurements indicate that the level at this one position approximates the room average.

In the studies reported in the literature, the uncertainties in the estimation of spatially averaged sound pressure level within the receiving room are not well addressed. In a number of previous studies, the level corresponding to a single microphone position in the center of the room was used as an estimate of the spatial average sound pressure level [8,10,11]. Also cited in previous studies is the use of one or more microphones placed along a diagonal of the receiving room at a point one-third of the length of the diagonal away from a corner of the room [7,12]. Although this microphone position has been advocated in the literature [16], data relating sound pressure levels measured at these points to the level that would be obtained from a comprehensive spatial average of mean-square sound pressure are not available.

Interior microphone positions used in measurements made to assess interior noise exposure are not well documented in the literature. In many studies, the location of the interior microphone is not specified at all. In one recent study [15], two microphone positions were used, one at the geometric center of the room, and one at a typical listener location such as an armchair or near the head of a bed; however only the averages of these two interior levels are reported.

3. Measurements of Noise Intrusion Reduction

As discussed in Sec. 1, the purpose of the outdoor-to-indoor sound isolation measurements in this study was to determine how outdoor traffic noises are modified when heard by indoor listeners. In order to achieve this specialized purpose, Noise Intrusion Reduction (NIR) was defined in Sec. 2.1 and measurement and analysis procedures were developed which varied from other procedures used in measuring building sound isolation in several ways, including choice of noise source, outdoor microphone placement, indoor microphone placement, and data reduction. The procedures used to determine NIR are presented in the remainder of this section.

3.1 Measurement Procedure

In order to determine Noise Intrusion Reduction, simultaneous magnetic tape recordings were made of sound pressure outside and inside each test house during a vehicle passby. The instrumentation used to acquire the simultaneous recordings is illustrated in Fig. 1.[1] Sound pressures were recorded using seven microphones, corresponding to three positions outdoors and four indoors. The signal on each of the seven channels was amplified and monitored to maximize the usage of the dynamic range of the FM magnetic tape recorder.

The positioning of the seven microphones relative to a hypothetical house is illustrated in Fig. 2. Of the four interior microphones, one was always positioned 1.0 meter from a window which faced the street upon which the vehicle passby occurred. This reference microphone was adjusted to be 1.2 meters above the floor. As it was intended to characterize sound isolation, as it relates to the noise exposure of listeners, the remaining three microphones were placed above seating positions throughout the room. These seating positions corresponded to the existing position of furniture (i.e., sofas and chairs) in the receiving room. Each microphone was centered above the seat of a particular piece of furniture and adjusted to be 1.0 meter above the floor, approximating typical ear height for seated listeners. The interior of Test House No. 9 is illustrated in Fig. 3.

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[1] Commercial instruments are identified in this report in order to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the equipment identified is necessarily the best available for the purpose.

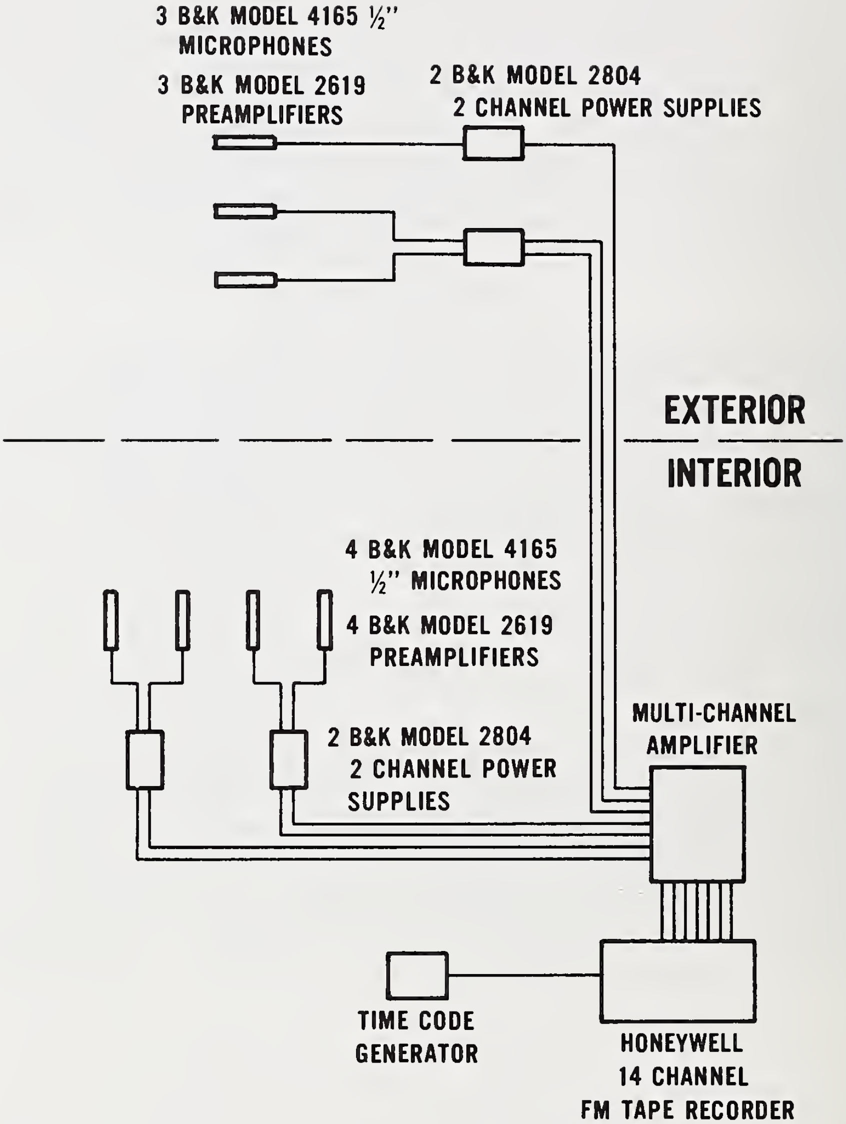

Figure 1. Schematic diagram of data acquisition system.

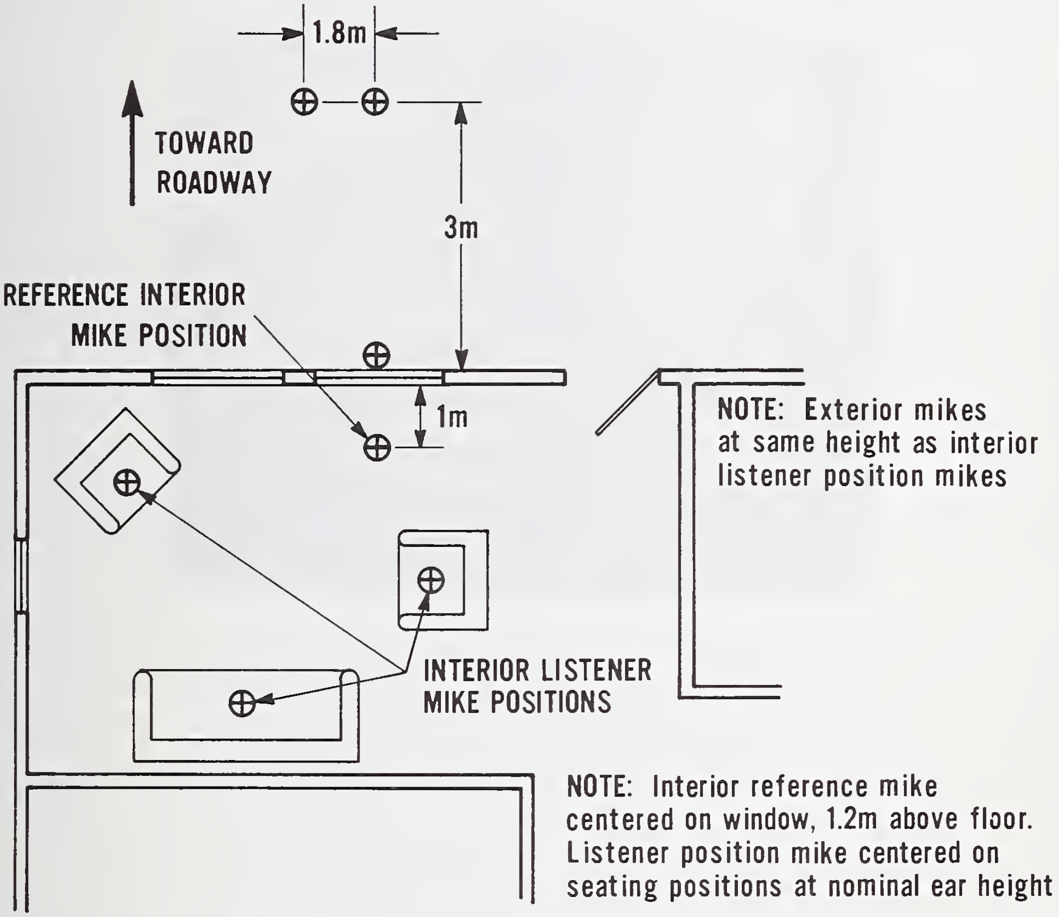

Figure 2. Schematic diagram showing exterior and interior microphone positions for a hypothetical house.

Figure 3. Placement of interior microphones at Test House No. 9.

Of the three outdoor microphones, two were positioned at a distance of 3.0 meters from the front facade of the house. The 3-m distance was selected to minimize variations in the measured sound levels, due to the presence of the reflecting plane of the building, for the frequency range from 50 to 4,000 Hz (see also Sec. 6.1). Two microphones were used at the 3-m distance to avoid reliance on a single microphone channel and to obtain some indication of the spatial variation of the exterior sound field.

The 3-m microphones were separated by a distance of 1.8 meter. This separation was selected to be greater than an acoustic wavelength for frequencies above 250 Hz where spatial variation is expected to be most pronounced. The separation was also selected to be on the order of the dimension over which irregularities in the building surface are likely to occur. The third outdoor microphone was positioned within 4.5 cm of the building facade for most of the test houses. This distance is the closest that the microphone could be placed to the facade as the microphone windscreen used had a radius of 4.5 cm. (For comparison to measurements at the 4.5 cm position, at two of the test houses distances of 15 cm and 160 cm were used). The purpose of this third exterior microphone was to provide data which could be compared to those obtained at 3 m to afford evaluation of the effect of microphone placement relative to an exterior building surface. All three outdoor microphones were adjusted in height to be approximately level with the interior listener position microphones. The placement of the three exterior microphones is illustrated in Fig. 4 for the test house shown in Fig. 3.

As the overall purpose of the program is to evaluate human response to traffic noise, the noise of vehicular passbys was chosen as the exterior noise source. It was further decided not to use local traffic in the vicinity of potential measurement sites, but rather to generate the exterior sound field with a passby of an NBS truck. This method was preferred because in those situations where there was sufficient local traffic to provide suitable interior sound levels, the background noise level in the house in the absence of vehicular noise could not be determined due to the continually-present traffic noise.

The vehicle used as a noise source is shown in Fig. 5 as it was driven by Test House No. 9. The vehicle was an International Harvester step-van with a V-8 engine, 4-speed manual transmission, and a maximum gross vehicle weight of 10,000 lbs. This vehicle had dual rear wheels with mud and snow tires and single front wheels with rib tires. For all the test houses except No. 1, the truck was driven past the house from left to right as viewed from the front of the house. For House No. 1, the passby was from right to left. In all cases, the vehicle was driven as close as possible to the edge of the roadway nearest the house.

For the nominally 48 km/hr (30 mph) passbys that were used, it was found that the truck alone produced sufficient noise in the frequency range from 50 to 1000 Hz to be measurable inside houses. However, above 1000 Hz,

Figure 4. Placement of exterior microphones at Test House No. 9

Figure 5. Passby of test vehicle at Test House No. 9.

where buildings provide more sound isolation, the passby noise of the vehicle alone produced insufficient signal to be measured adequately indoors. To remedy this situation, the high frequency portion of the truck spectrum was supplemented with "pink noise" broadcast through loudspeakers. The loudspeakers were placed on the van step on the opposite side of the vehicle from the driver position. At this position, the loudspeakers were approximately 0.75 m above the roadway. The position of these loudspeakers on the truck is pictured in Fig. 6. The effect of the supplemental pink noise on the 1/3-octave band spectrum of the truck as recorded outdoors is illustrated in Fig. 7 for a passby at Test House No. 9. With the addition of the supplemental pink noise, sufficient interior signal was obtained to determine the Noise Intrusion Reduction over the frequency range from 50 to 4,000 Hz for all of the test houses.

Prior to the recording of passby sound levels at each of the nine test houses, calibration signals were recorded for each of the seven data acquisition microphones, using a Brüel and Kjaer (B & K) Type 4220 Pistonphone, producing 124 dB, re 20 μPa, at 250 Hz, for a minimum of 10 seconds after the signal stabilized. After calibration, B & K Type 0237 windscreens were placed on the three exterior microphones.

To minimize the intrusion of environmental noise events other than the truck passby, two-way radio communication was maintained between the recording team and the driver. In this manner, the truck passbys were coordinated with data acquisition so that data were only obtained during the passbys. At least five truck passbys were recorded at each house with all exterior windows and doors closed. Three additional passbys were conducted with either several windows or an exterior door open. During the course of the recordings, an ambient noise recording was also made on all seven microphone channels in the absence of the truck and of any observable environmental noise source.

For all the recordings at each of the houses, the wind speed was less than 4 m/sec. The outdoor temperature ranged from 18 to 30°C. In all cases, the roadway surface was dry.

At each of the test houses, supplemental physical data regarding the test house and room were obtained. Photographs were taken to indicate the positioning of the four interior microphones relative to the room and furniture. These photographs were also intended to afford information regarding furnishings in the room and their orientations. In addition to photographs, a sketch of the room floor plan was drawn and room dimensions noted (see Appendix A). The location, dimension, and type of exterior doors and windows were noted. Photographs were taken of the exterior of the house to indicate the positioning of the exterior microphones and to provide overall orientation of the street and house. The distance from the front of each house to the near edge of the roadway was measured and noted. Only a few sample photographs have been included in this report.

Figure 6. Interior of test vehicle showing placement of loudspeakers used for supplemental pink noise.

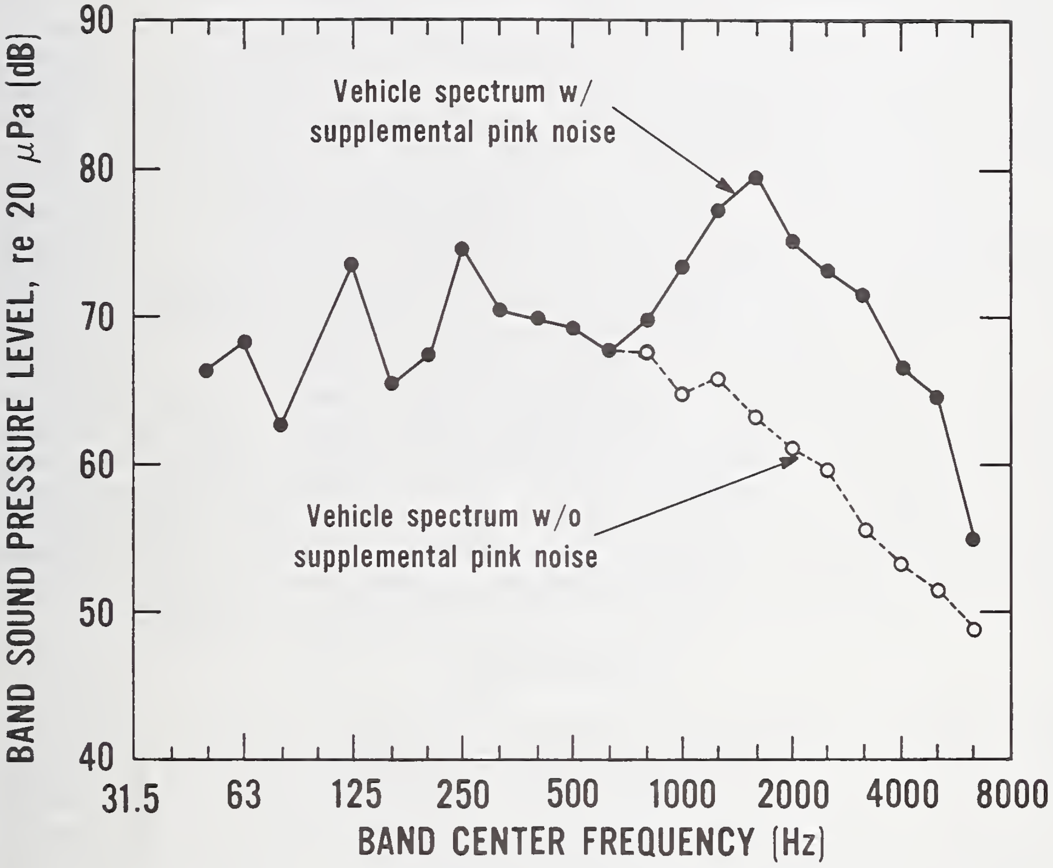

Figure 7. One-third octave band sound pressure level spectra as produced outdoors during a passby of the test vehicle with and without supplemental pink noise.

3.2 Measurement Sites

Recordings of outdoor and indoor sound levels were made at nine different single-family houses in the metropolitan Washington, D.C. area. These houses were selected to include several samples of two common construction types, wood frame and frame with brick veneer. For each type of construction, other parameters were varied, such as window type, distance to roadway, presence of exterior doors, and amount of brick facing. The parameters characterizing the nine houses are summarized in Table 1. With the large number of possible combinations of construction variables, not all parameters could be varied independently over the sample set of nine houses. From Table 1, it will be noted that three all-frame houses, five frame houses with brick veneer, and one frame house with stone veneer were tested. Of the brick veneer houses, three had brick veneer all around the house up to the top of the windows, one had brick only to the front (facing the roadway) of the house, and one had brick veneer over the entire exterior surface. For both all-frame and brick veneer construction types, houses with and without storm windows were tested. In the set of test houses, storm windows were not in place on four houses and were in place on four houses. The remaining house had storm windows on all windows except on one large, fixed window. This house is referred to as having "partial" storm windows. The set of houses also included two houses with exterior doors to the side of the house and two with no exterior doors in the test room. All of the houses tested had windows facing the roadway with five also having windows to the side of the house. In all cases, the test room was either a living room or living/dining room combination. The floor plans of the test rooms for the nine houses are given in Appendix A.

3.3 Data Reduction

The exterior and interior analog sound pressure recordings for each of the nine test houses were reduced to 1/3-octave band sound pressure levels using three different processing methods. The first method was designed to produce 1/3-octave band sound pressure level time histories for the individual vehicle passbys for each of the microphone positions. This reduction was accomplished by playing the tape recordings back into a General Radio Model 1921 real-time 1/3-octave band analyzer. This analyzer utilizes "true" integration, i.e., levels corresponding to the average mean-square sound pressure over a specified integration time are obtained. For the purposes of this study, an integration time of 0.2 seconds was used. The resultant sound level time histories were printed and simultaneously recorded digitally on magnetic tape under computer control.

The second method of obtaining 1/3-octave band sound pressure levels from the recorded pressure signals was designed to obtain the maximum sound pressure level occurring in each 1/3-octave band during an individual vehicle passby for each of the microphone positions. This reduction was accomplished using a B & K Type 2131 Digital Frequency Analyzer. Using the "max hold" feature of the analyzer, the maximum (1.0 second time constant) level occurring in each 1/3-octave band was detected and held. The resultant maximum levels were printed on a teletype controlled by the analyzer.

Table 1. Summary of test house parameters

House No.	Construction	Outside Door	Window Area Front (m^2)	Window Area Side (m^2)	Total (m^2)	Storm Window	Room Volume (m^3)	Distance To Street (m)
1	Brick Veneer (Partial Height[a/])	Front	3.4	0	3.4	Partial	55	11
2	Brick Veneer (Full)	None	3.6	0	3.6	None	64	20
3	Brick Veneer (Partial Height[a/])	Front	3.3	0	3.3	Full	64	61
4	Stone Veneer (On Front Only)	None	3.4	0	3.4	None	54	20
5	Frame	Front	2.7	1.1	3.8	Full	43	13
6	Brick Veneer (On Front Only)	Side (2 doors)	2.3	2.7	5.0	None	72	14
7	Brick Veneer (Partial Height[a/])	Front	3.5	1.1	4.6	Full	51	15
8	Frame	Side	3.9	2.6	6.5	None	83	24
9	Frame	Front	4.5	1.1	5.5	Full	48	15

a/ To Top of Window

The B & K analyzer was also used for the third method of data reduction. For this method, the average 1/3-octave band levels were obtained by averaging the squared sound pressure over an 8.0 second interval. The 8.0 second time interval was found to be sufficiently long to include all of the A-weighted sound levels occurring between the 10-dB-down points of the passby at all of the microphone positions. The average level occurring in the 8.0 second time interval was then used to compute the sound exposure level[1] (SEL) of the passby at each microphone position.

Prior to calculating NIR values from the 1/3-octave band sound pressure level data, the mean-square pressures obtained at the two exterior 3-m microphones were averaged. This was done to minimize the uncertainty due to spatial variation of the measured sound pressure levels for these two microphone positions. Further discussion of the variation observed between the two 3-m microphone positions is provided in Section 5. Other than averaging the data for the two 3-m microphone positions, no corrections were applied to exterior data to compensate for the presence of the building surface. Also, no correction was applied for spherical divergence between the microphone position and building surface because the difference in level due to this phenomenon is approximately frequency independent.

After averaging the 1/3-octave band pressure levels obtained from the two 3-m exterior microphones, NIR values were calculated by subtracting the interior 1/3-octave band sound pressure levels measured at each of the four microphone positions from the corresponding average exterior level at 3 m. This calculation was performed on the data obtained using the three reduction techniques discussed above, thus forming three distinct data sets. The characteristics of these three data sets are summarized in Table 2.

Data Set No. 1 was formed using simultaneously occurring exterior and interior levels corresponding to the time at which the interior A-weighted level was at a maximum at the interior reference microphone position. This time in the passby was chosen to optimize the signal-to-noise ratio as measured indoors. Such optimization was necessary since it was found that for some houses with either particularly good isolation properties or with large distances between the house and roadway, measurable sound pressure levels in each of the 1/3-octave bands were generated indoors only for a very short time near the time of the maximum interior A-weighted sound level. At the time of maximum interior A-weighted sound level, there was sufficient signal-to-noise ratio in all 1/3-octave bands to avoid background noise corrections for all test houses except Nos. 1 and 3. In House No. 3, which was 61 m from the roadway, sufficient signal was not present at the time of maximum interior A-weighted sound level to allow computation of Noise Intrusion Reduction in the 1/3-octave bands centered from 315 to 800 Hz, even with corrections for background noise.

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[1]Sound exposure level is defined as:

$$\mathrm{SEL} = 10\ \ell og_{10}\left[\frac{1}{t_o}\int_0^T 10^{L/10}dt\right] ,$$

where T is the duration of the event in seconds, L is the 1/3-octave band or the A-weighted sound pressure level, re 20 μPa, as a function of time, and $t_o \equiv 1.0$ second is a reference time [2].

Table 2. Summary of Noise Intrusion Reduction data set parameters

Data Set No.	Averaging Time (s)	Sample Used in NIR Calculation
1	0.2	1/3-octave band data at time of maximum interior A-weighted sound level
2	1.0	Maximum 1/3-octave band (indoor and outdoor) sound pressure level regardless of time of occurrence
3	8.0	Approximate sound exposure level (indoor and outdoor) in each 1/3-octave band

Data Set No. 2 was formed using the maximum level occurring in each 1/3-octave band for each microphone position during the passby, regardless of when the maximum occurred. For this type of data reduction, sufficient signal-to-noise ratio was obtained in all 1/3-octave bands to avoid any need for correction for background noise, except for Test House No. 1.

Data Set No. 3 was formed using the 1/3-octave band sound exposure levels determined for the individual exterior and interior microphone positions for passbys of Houses No. 6 and No. 8. This calculation was only done for these two houses since the other seven houses did not provide sufficient signal-to-noise ratio in 1/3-octave bands over the 8.0 second time interval.

The numbers of passbys for which NIR values were calculated for each Data Set are summarized in Table 3. The results of these calculations are presented in Appendices B, C, and D and discussed in Sections 4 and 5. For Data Set No. 1, 1/3-octave band NIR values were calculated for House No. 8 at different instances during the passby using the 1/3-octave band time history data. These additional instances in time were at 2.8 and 1.4 seconds before the maximum interior A-weighted level and at 1.4 and 2.8 seconds after the maximum.

Table 3. Summary of cases analyzed for the three different data sets.

Test House	Windows and Doors	Number of Passbys Analyzed		
		Data Set No. 1	Data Set No. 2	Data Set No. 3
1	Both closed	1	1	-
2	Both closed	1	4	-
2	Windows open	-	1	-
3	Both closed	1	1	-
4	Both closed	1	1	-
5	Both closed	1	1	-
6	Both closed	1	1	1
7	Both closed	1	1	-
8	Both closed	1[a]	1	1
9	Both closed	5	5	-
9	Door open	1	1	-

[a] NIR values were also calculated for different instances during the passby (see text).

4. Average Values of Noise Intrusion Reduction

In order to use the results presented in Appendices B, C, and D to develop a filter shape corresponding to the "typical" modification of outdoor traffic noise spectra as received by listeners located indoors, some method must be used to combine the results for individual microphone positions at the nine different houses. For the purposes of the current study, this combination was performed by first determining the spatial average Noise Intrusion Reduction (NIR) values for each house individually. Using these spatial average values, average NIR values for the set of nine houses were calculated. Discussion of several averaging techniques and values resulting from the averaging is presented in this section. Also included in this section is a comparison of the average values obtained in the current study with noise isolation data reported in the literature.

4.1 Average Noise Intrusion Reduction for Individual Houses

4.1.1 Averaging Technique

For each of the individual test houses and for each of the data sets of Table 2 it was desired to combine the NIR values determined for the three interior listener position microphones into one set of 1/3-octave band NIR values representing each house. These spatially averaged values are of particular concern because significant variation in NIR values among the three interior listener positions in individual houses was observed. Variation was most pronounced in the lower 1/3-octave bands, with variations in some cases of more than 10 dB in the 1/3-octave bands centered from 63 to 200 Hz. Above 800 Hz, variations of up to about 5 dB were found to occur. Spatial variations are further examined in Sec. 6.2.

Combination of the NIR values for individual houses could be performed using any of several methods. One possible method of spatially combining values is to represent the house by the lowest values of NIR, thus representing the most severe noise exposure case. These lowest values might be those obtained from some determined "worst" case microphone or those obtained on a 1/3-octave band basis using the worst case of any of the three positions. A second possible method of consolidation is to perform some type of averaging of the three sets of values.

For the purposes of current study, it was decided to compute an NIR corresponding to the values that would be obtained by subtracting the average level (based on averaging the squared sound pressures) of the three interior listener microphone positions from the average level of the two 3-m exterior microphone positions:

$$\mathrm{NIR} = 10\ \ell og \left[\frac{1}{2} \left(10^{L_{a,1}/10} + 10^{L_{a,2}/10} \right) \right] - 10\ \ell og \left[\frac{1}{3} \left(10^{L_{b,1}/10} + 10^{L_{b,2}/10} + 10^{L_{b,3}/10} \right) \right] , \qquad (4)$$

where $L_{a,m}$ is the exterior sound pressure level at microphone position m and $L_{b,n}$ is the interior sound pressure level for the microphone at listener position n, This method of representing the average Noise Intrusion Reduction for each house was selected because the averaging represented in Eq. (4) corresponds to that specified in the ISO and proposed ASTM standards for sound insulation measurements [4,5] and also is the same as that used in a recent study of "dwelling attenuation" for purposes of assessing occupant exposure to exterior transmission line noise [15].

From Eq. (4), NIR values averaged over the three interior listener positions were calculated and are presented in Appendices B, C, and D for each of the nine test houses and passby cases for which individual microphone data are reported.

4.1.2 Comparison of Average Values for Data Sets No. 1, 2, and 3

Prior to combining the results of measured noise reduction into a single outdoor-to-indoor filter shape, several aspects of the individual house average values should be considered. One of these is the relationships among average NIR values determined for the three data sets of Table 2. The averages corresponding to these three values of NIR are plotted in Fig. 8 for one passby at House No. 6. For the case shown in this figure, there are only slight differences between the values corresponding to Data Sets No. 2 and No. 3. These differences are typically about 1 dB and always less than 2 dB. The values for Data Set No. 1 vary from those of the other two data sets. For some 1/3-octave bands, the difference between values from Data Set No. 1 and the other two sets is as much as 7 to 8 dB, with typical differences of 2 to 3 dB at the higher frequencies. Averages corresponding to the three types of NIR values are plotted in Fig. 9 for House No. 8. As in the previous case, the differences between the values of Data Set No. 2 and Data Set No. 3 are uniformly small, at most 2 dB, and the difference between the values of Data Set No. 1 and the other two sets is more pronounced, being as much as 5 to 6 dB for some 1/3-octave bands.

Departures of the values for Data Set No. 1 from the values for Data Set No. 3 are expected for two reasons. First, Data Set No. 3 corresponds to an average over the varying incidence angle of the exterior sound. Second, the measurement uncertainty in the lower 1/3-octave bands is greater for the simultaneous levels of Data Set No. 1.

The variation from one passby to another of the NIR values obtained for Data Sets No. 1 and No. 2 was also examined. For House No. 9, five consecutive vehicle passbys were reduced to average NIR values for both Data Sets No. 1 and No. 2. The range of 1/3-octave band average NIR values resulting from the five individual passbys of Test House No. 9 for Data Set No. 1 is shown in Fig. 10. From this figure, it is seen that, from run-to-run, values in individual 1/3-octave bands typically range over about 5 dB. Below 400 Hz, this range

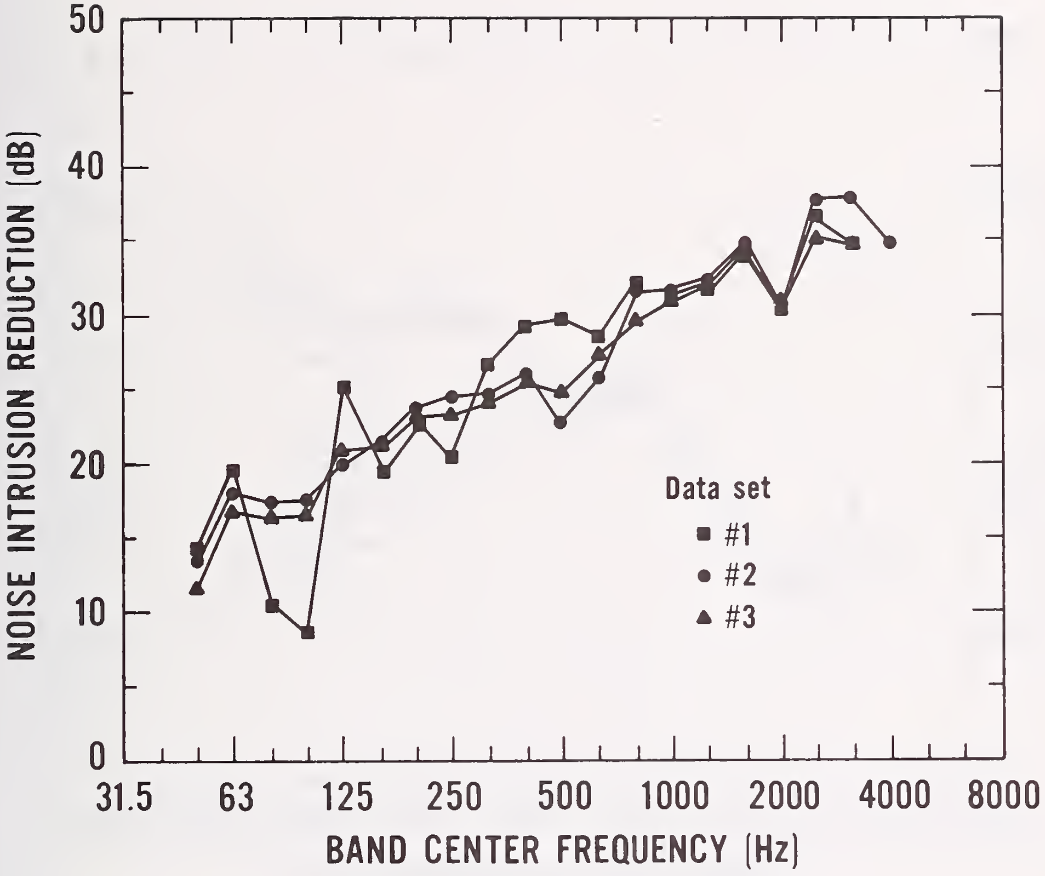

Figure 8. Noise Intrusion Reductions, for the three different data sets, at Test House No. 6.

Data Set No. 1. Computed from simultaneous 1/3-octave band levels at the time of maximum interior A-weighted level.

Data Set No. 2. Computed from the maximum 1/3-octave band levels, regardless of when they occurred.

Data Set No. 3. Computed from 1/3-octave band sound exposure levels.

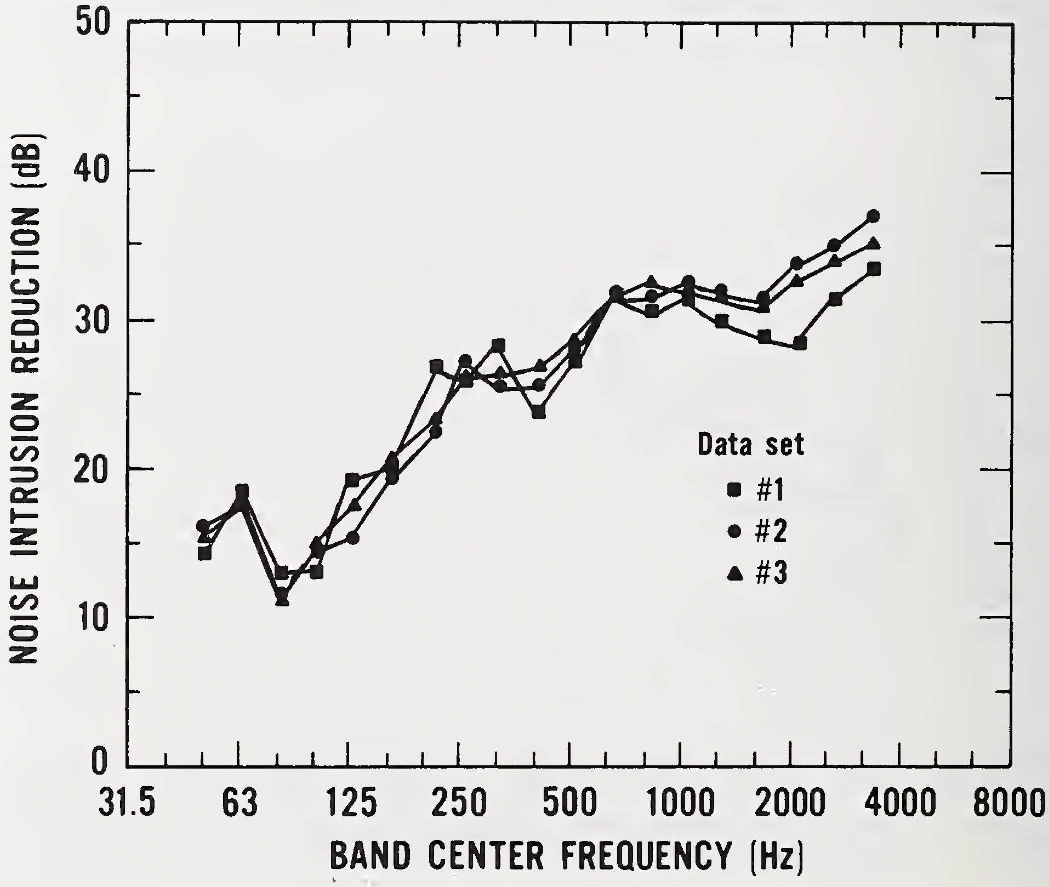

Figure 9. Noise Intrusion Reductions, for the three different data sets, at Test House No. 8. (The three data sets are defined in the text and in the caption for Fig. 8.)

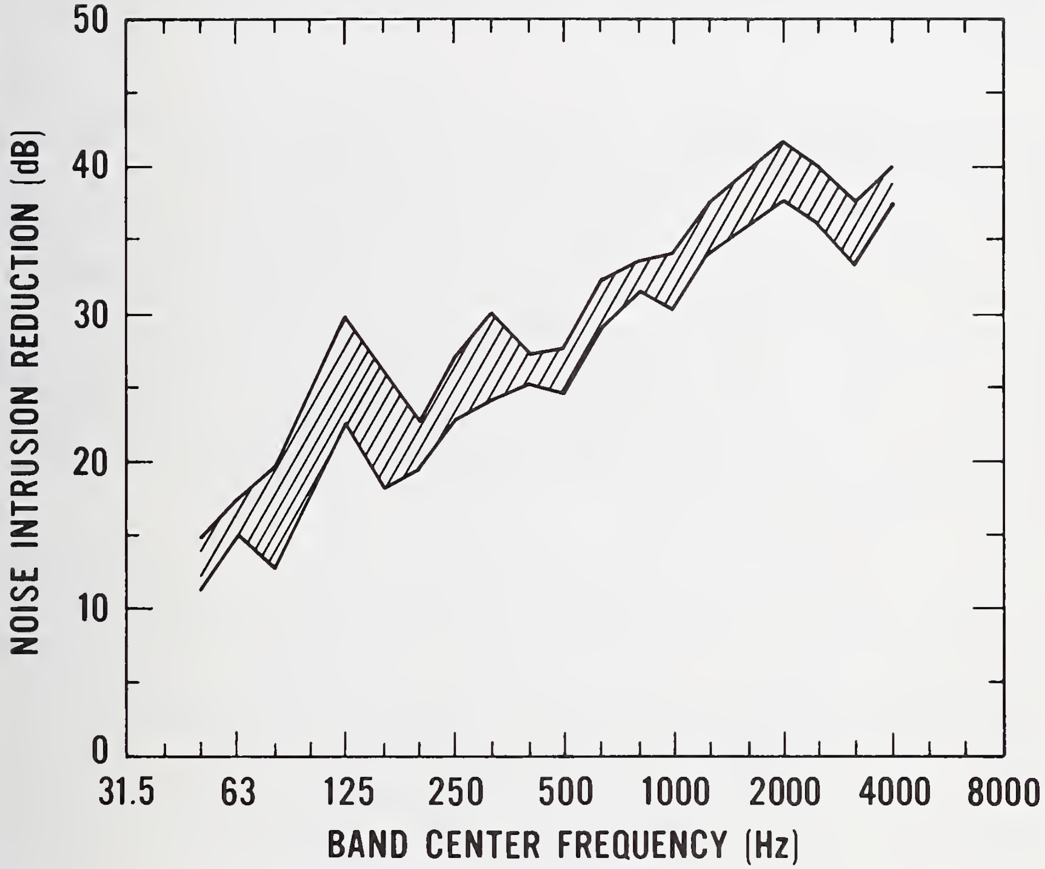

Figure 10. Range of Noise Intrusion Reduction values, for Data Set No. 1, for five passbys of Test House No. 9.

increases to as much as 6 to 7 dB. For comparison, the range resulting from the same five passbys of Test House No. 9 determined using the differences in maximum level (for Data Set No. 2) is provided in Fig. 11. From this figure it is seen that the range from run to run using the data reduction technique of Data Set No. 2 is less than 2 dB above 250 Hz and at most 5 dB below 250 Hz. Since Data Sets No. 2 and 3 are practically identical (see Figs. 8 and 9), the range is similarly small for Data Set No. 3. The range resulting from the four passbys of Test House No. 2 is shown in Fig. 12. Above 160 Hz, the range is less than 3 dB for all bands. At and below 160 Hz, the range varies from 1.5 dB at 63 Hz to 7 dB at 125 Hz. For comparison, for Test House No. 9, above 125 Hz the range was less than 3 dB while at and below 125 Hz it varied from 2 dB at 50 Hz to 5 dB at 100 Hz.

The results presented in Figs. 8 and 9 can be used to compare more generally the three data reduction techniques. The use of spatially averaged NIR values obtained from sound exposure levels to determine the house attenuation "filter" shape would have the advantage of averaging over incidence angles for the exterior sound field and would be directly relatable to the commonly used average (equivalent) sound level. Also, because the SEL-related values of NIR correspond to average sound level, the use of this data reduction technique is consistent with the ISO and proposed ASTM standards [4,5]. However, as discussed previously, sufficient signal-to-noise ratio to determine the SEL data in most of the test houses could not be maintained, even with supplemental pink noise, for the duration of the passby. It is anticipated that such signal-to-noise limitations would occur in many cases where vehicular noise sources are used unless exceptionally loud or close vehicles are present or the test house has quite poor sound isolation.

In the further combination of the NIR values to obtain a single filter shape, only those values corresponding to the difference in maximum level (Data Set No. 2) were used. These values are used because of their agreement with the Data Set No. 3 values obtained for two of the test houses, their run-to-run consistency, and their maximization of signal-to-noise ratio. The values of Data Set No. 2 display quite close agreement to the values of Data Set No. 3 because the largest contribution to the SEL in any one band occurs when the level in that band is at its maximum value. In addition to the close correspondence to the SEL-related NIR values, the maximum level values of Data Set No. 2 also have the advantage of providing the greatest signal-to-noise ratio of the three data reduction methods.

4.2 Average Noise Intrusion Reduction for All Nine Test Houses

4.2.1 Averaging Technique

To combine further the average NIR values of Data Set No. 2 so as to obtain an appropriate average NIR for the set of nine test houses, it was necessary to select a method for averaging these nine sets of values. To perform such an average, three methods were considered, corresponding to the following equations:

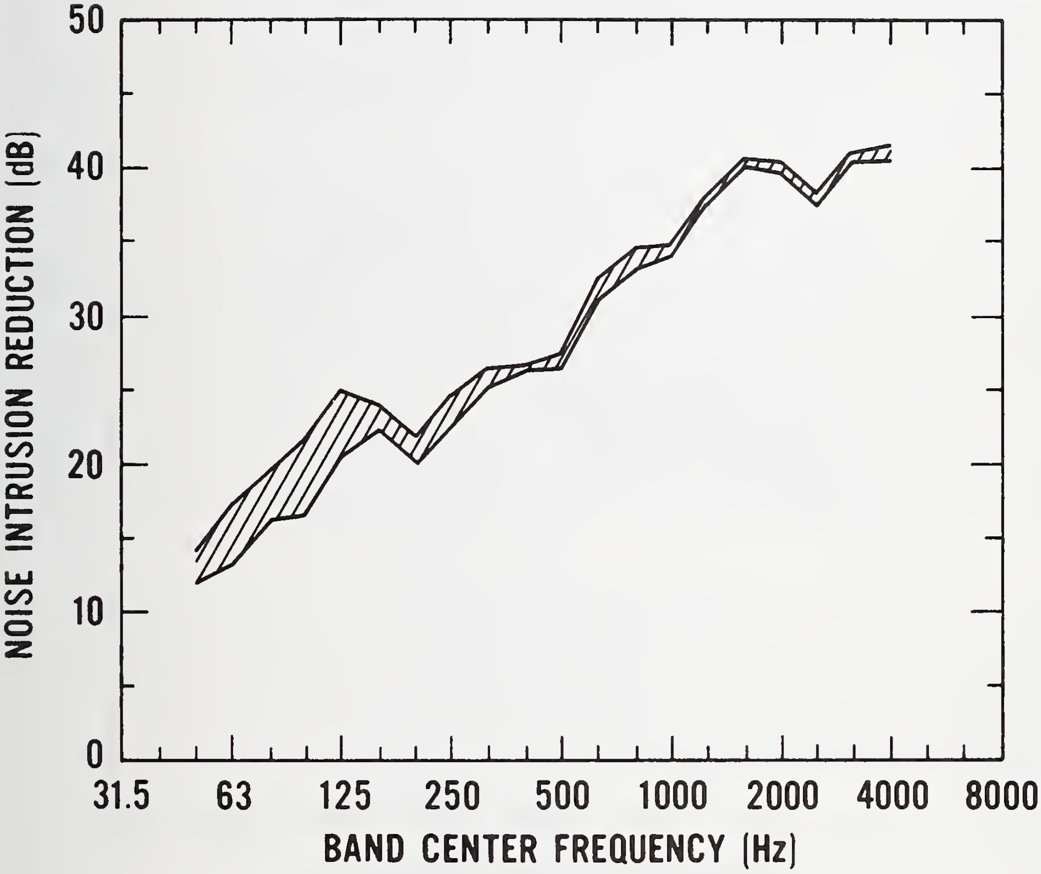

Figure 11. Range of Noise Intrusion Reduction values, for Data Set No. 2, for five passbys of Test House No. 9.

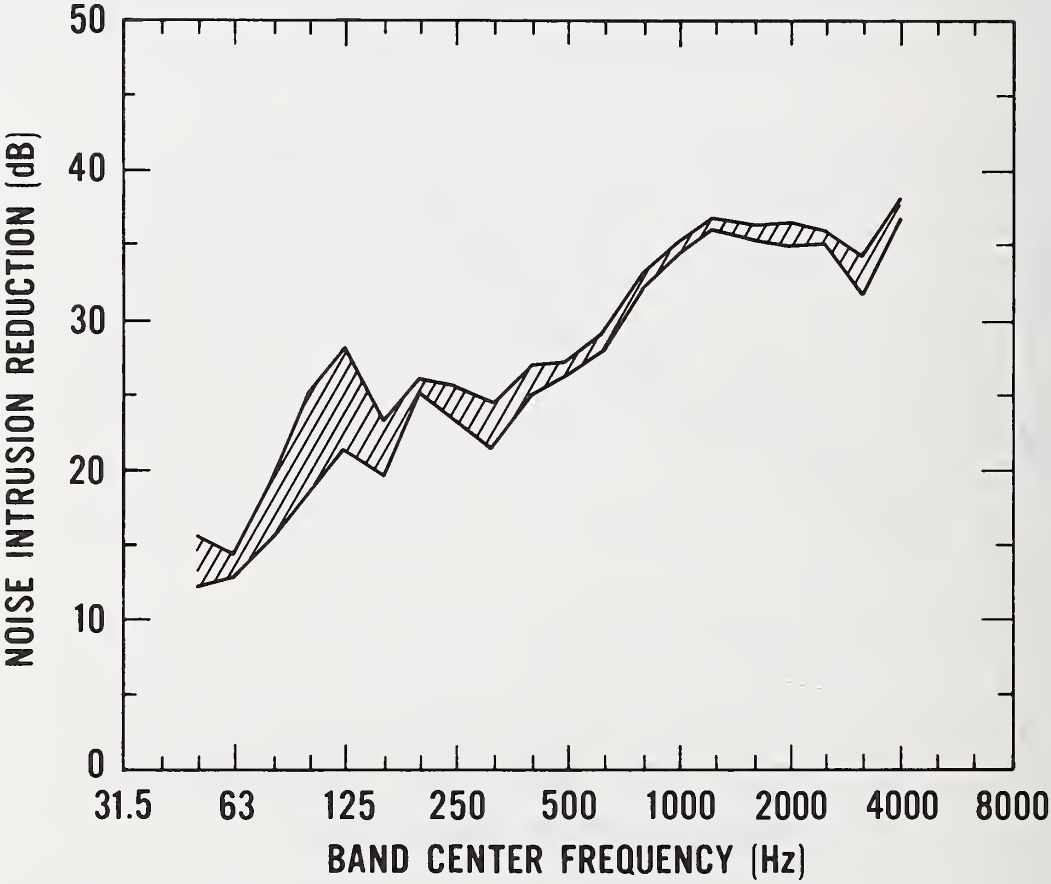

Figure 12. Range of Noise Intrusion Reduction Values, for Data Set No. 2, for four passbys of Test House No. 2.

$$\overline{NIR} = \frac{1}{n}\left(NIR_1 + NIR_2 + \ldots + NIR_n\right), \tag{5}$$

$$\overline{NIR} = 10 \, \ell og \left[\frac{1}{n}\left(10^{NIR_1/10} + 10^{NIR_2/10} + \ldots + 10^{NIR_n/10}\right)\right], \tag{6}$$

and

$$\overline{NIR} = -10 \, \ell og \left[\frac{1}{n}\left(10^{-NIR_1/10} + {}^{-NIR_2/10} + \ldots + 10^{-NIR_n/10}\right)\right], \tag{7}$$

where NIR_i is the value for the i-th house. These three equations correspond to different interpretations of the average values obtained.

Equation (5) is simply the arithmetic average of the NIR values. Equation (6) corresponds in concept to adjusting the exterior noise source for each house to a level which produces a specified (constant) level inside each of the houses, computing the resultant average exterior sound pressure levels, and subtracting the fixed interior level from the average exterior level. Equation (7) corresponds in concept to exposing the houses to a specified (constant) exterior noise environment, computing the resultant interior sound levels at all houses, averaging the interior mean-square sound pressure levels, and subtracting this average interior level from the specified exterior sound level to produce the "average" NIR.

Although the three averaging techniques discussed above are conceptually distinct, when applied to the NIR values for the nine test houses only minimal differences among the resultant average values were found. The average values for the nine test houses using each of the three methods are presented in Fig. 13. From this figure it is seen that Eq. (6) yields averages that are consistently higher than those from Eq. (7) and that the values resulting from Eq. (5) lie in between the values produced by Eqs. (6) and (7). Typically, the range of the average values in any one 1/3-octave band is about 2 dB except in the bands centered at 80, 100, and 125 Hz, where the range is 3 to 4 dB. It is further evident in Fig. 13 that the shapes of the three average noise reduction curves are nearly identical so that the distinctions among the averaging techniques are not critical for the purposes of the current study. For the current study, it was decided to use Eq. (7) to combine the NIR values for the nine test houses so as to produce a single filter shape.

4.2.2. Values of Average Noise Intrusion Reduction

The average (using Eq. (7)) NIR values in each 1/3-octave band for the set of the nine test houses are presented again in Fig. 14. Also indicated in Fig. 14 is the range of NIR values in each 1/3-octave band for average values for individual houses and the range of NIR values for individual microphone positions for all nine of the test houses. From Fig. 14 it is seen that the range of average NIR values for the individual houses is 10 dB or less in all 1/3-octave bands except those centered at 80, 100, and 125 Hz.

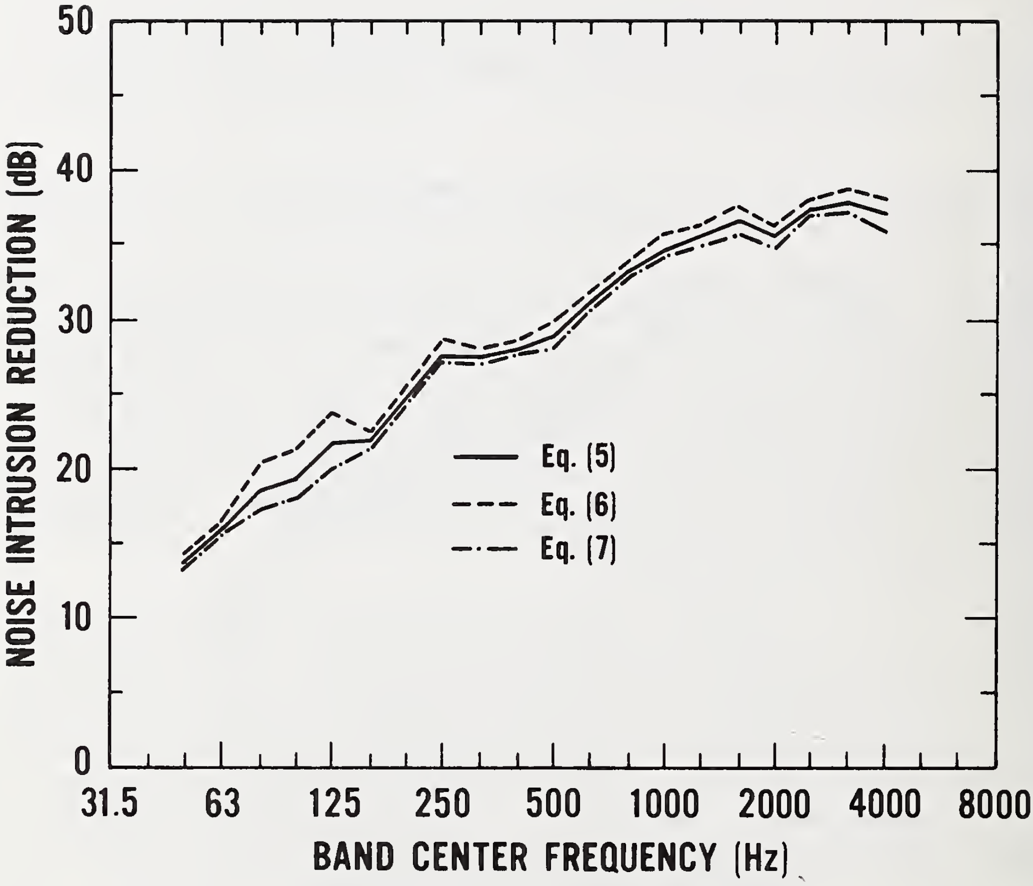

Figure 13. Noise Intrusion Reduction values averaged over all nine test houses using three different averaging procedures.

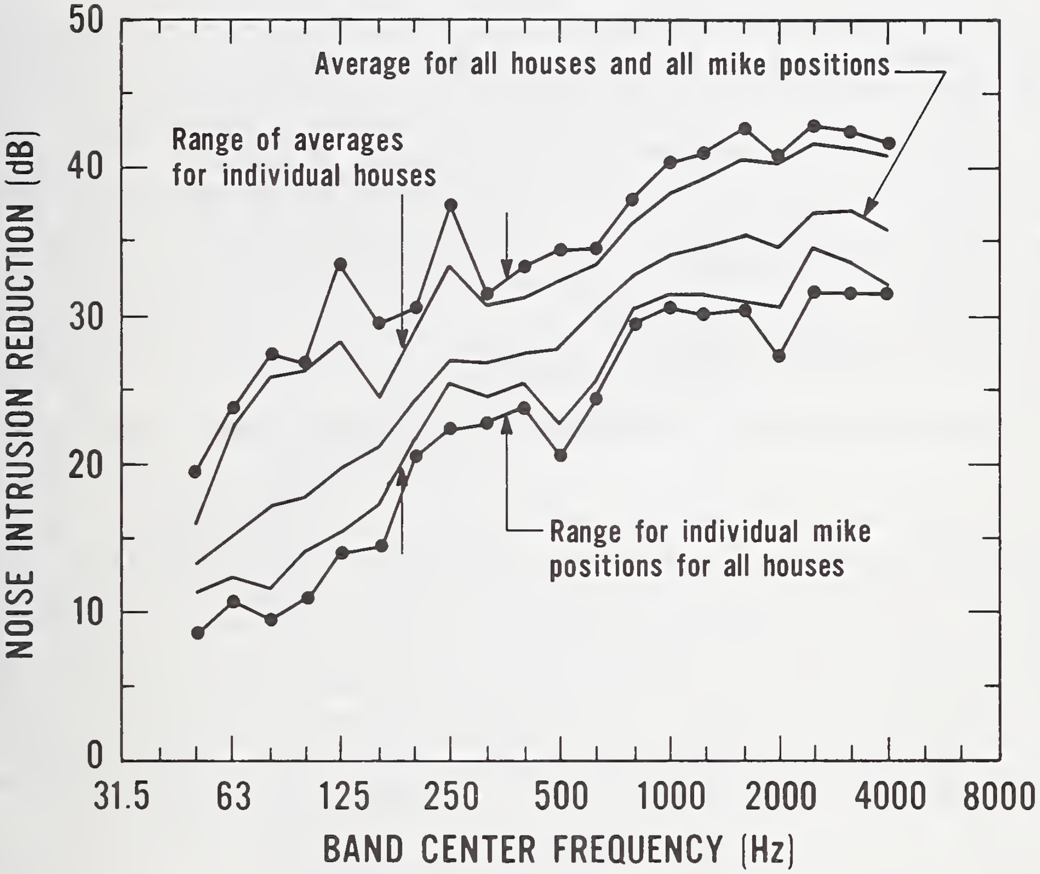

Figure 14. Average and range of Noise Intrusion Reduction values for all nine test houses.

The range of values for the individual microphone positions is consistently greater than the range of the (spatial) average values for the individual houses — typically it is about 10-12 dB with the maximum range of 19 dB occurring in the 125-Hz 1/3-octave band. From Fig. 14, it will also be observed that the shapes of all five of the curves, i.e., the two pairs of ranges and the overall average NIR, are quite similar except that below 250 Hz variations are more pronounced.

In calculating the nine-house average NIR values of Fig. 14, data from a single passby of each test house were used. Data from more than one passby of each test house might have been reduced and used to calculate the nine-house average, but it is believed that this would not significantly reduce the uncertainty in the nine-house average values. From Figs. 11 and 12, it is seen that the range of NIR values for several vehicle passbys is small, on the order of 3 dB for most 1/3-octave bands. Further, for any given test house, there is approximately equal likelihood that any one 1/3-octave band value for one vehicle passby would be above or below an average value for several passbys. Thus, when the values for nine houses are averaged, the small differences between values for a single passby and an average of passbys for any one house will tend to average out.

4.3 Comparison of the Average Noise Intrusion Reduction to Published Values of Sound Isolation

Published data on building sound isolation have been reviewed in order to determine the range of typically-occurring sound isolation values. For purposes of comparison to the current study, attention was restricted to those studies which reported the results of field measurements for buildings rather than laboratory measurements of the sound insulation properties of building elements, such as windows and wall construction. With this restriction, it was found that only a limited amount of spectral building sound isolation data is available in the literature. Of these reported data, most were obtained using aircraft flyovers as the source of exterior noise, with the remainder using traffic noise or controlled loudspeakers.

Published outdoor-to-indoor isolation data obtained for aircraft noise sources are presented in Figs. 15 through 17, along with the average Noise Intrusion Reduction curve from the present study. For the purposes of this comparison, the average NIR values from the current study have been reduced by 1.5 dB to account for average spherical divergence differences between levels measured at the 3-m exterior microphone position and those at the building surface. Further, for comparison with the published octave band data, the 1/3-octave band NIR values averaged over the nine houses in the present study have been combined into octave band values (the averaging being done in a manner analogous to that represented by Eq. (7). The resulting values are shown in Figs. 15 and 16. (Note that the data from the

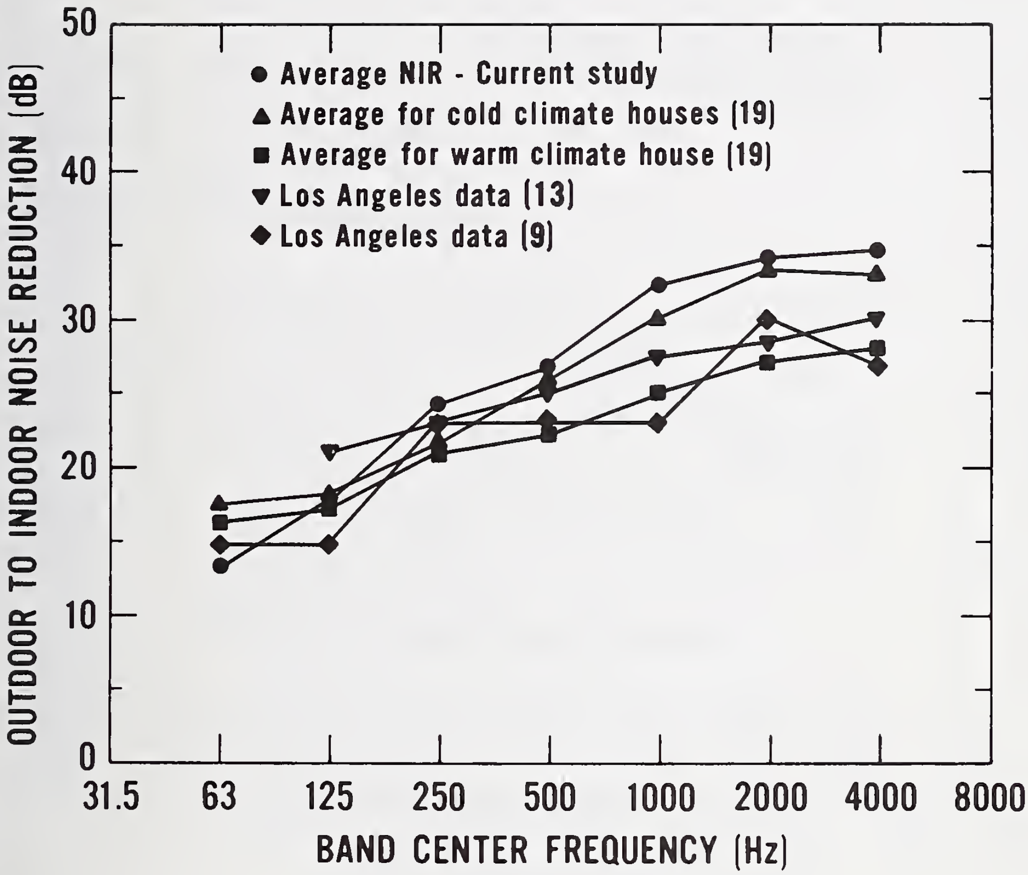

Figure 15. Comparison of average octave-band Noise Intrusion Reduction values from the present investigation with sound isolation values reported in the literature for aircraft noise.

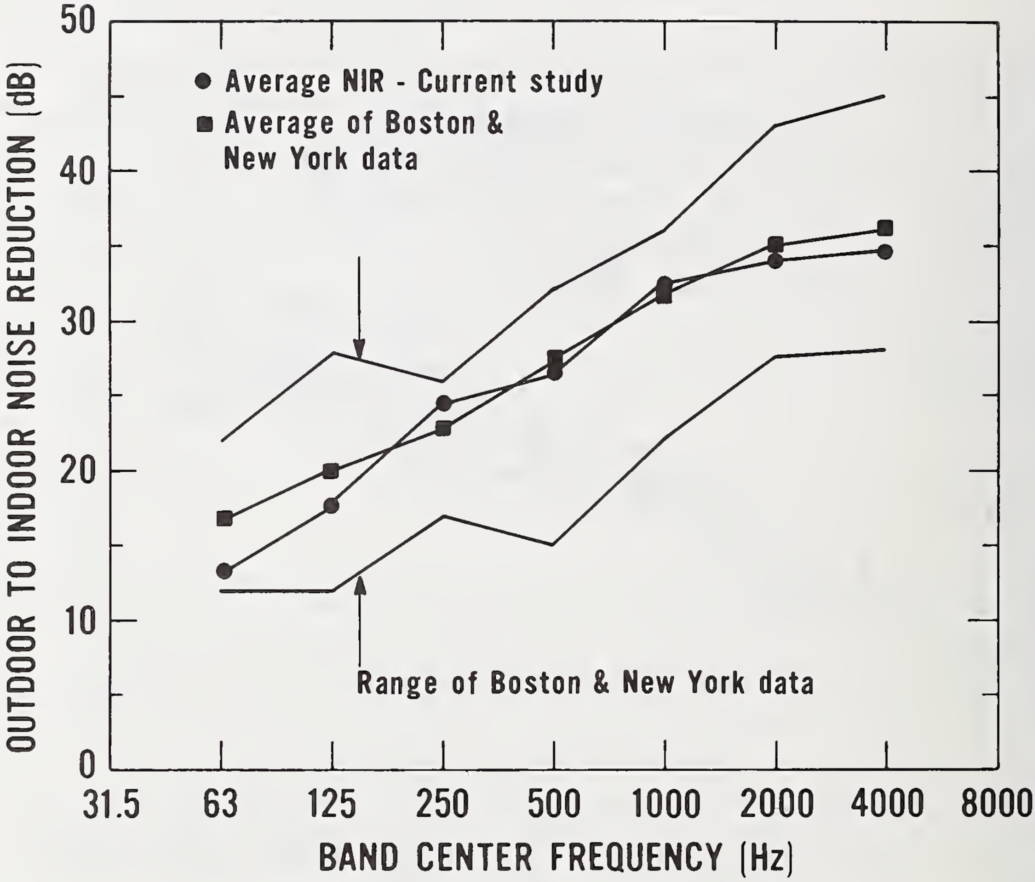

Figure 16. Comparison of average octave-band Noise Intrusion Reduction values from the present investigation with the average and range of sound isolation values reported in the literature for aircraft noise in the Boston and New York areas [27].

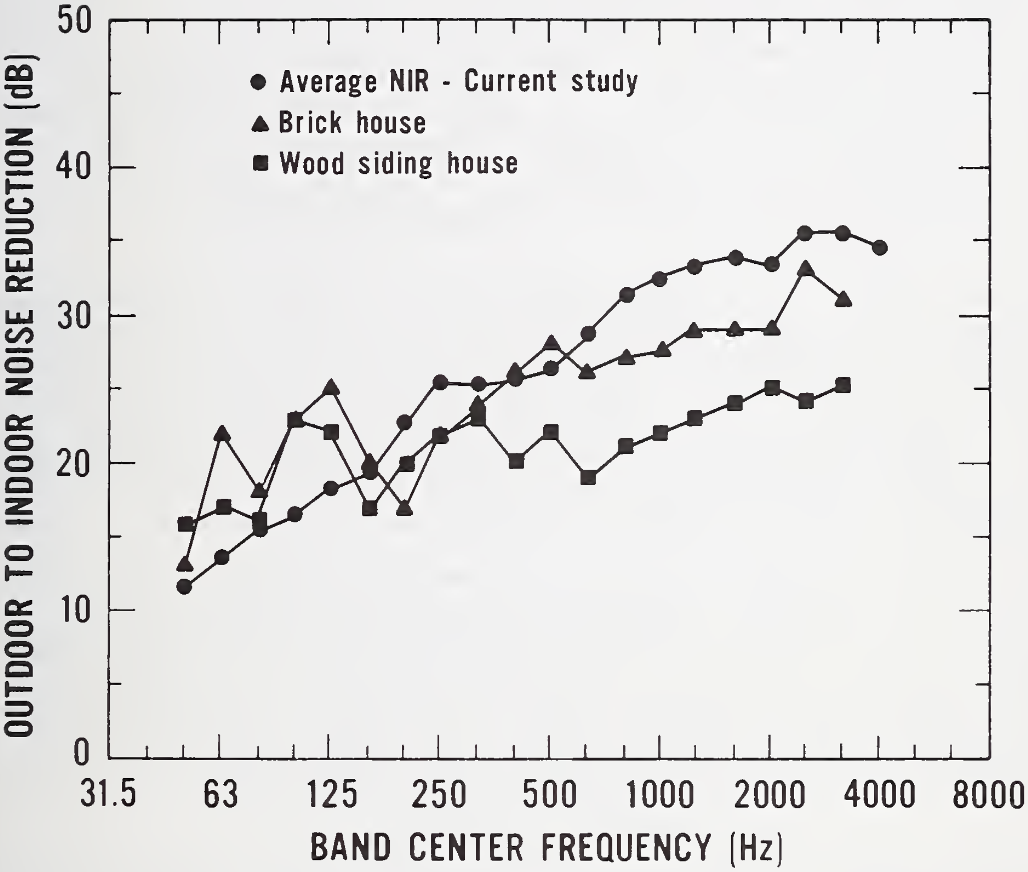

Figure 17. Comparison of average Noise Intrusion Reduction values from the present investigation with sound isolation values reported in the literature for brick and wood siding houses at Wallops Island, Virginia [17].

present study correspond to interior sound levels being averaged over listener positions; this is not generally the case for the previously-published data.) Presented in Fig. 15 are the results of a Society of Automotive Engineers (SAE) data summary document [19] and results of two studies performed in the Los Angeles area [9,13]. The average house sound isolation values compiled by SAE were grouped into those for warm and cold climates since it was found that houses in warmer climates tended to have (1) a larger ratio of window area to exposed wall surface, (2) windows not as tightly fitted, and (3) lighter weight roof construction. It will be noted that the data reported for the Los Angeles area are quite similar to the SAE warm climate average. Generally, the warm climate data display a flatter spectrum shape than those reported for the colder climates. This relative flatness is due to lower isolation in the middle and high frequencies in comparison to the SAE cold climate average. It should be noted that the average curve obtained in the present study is similar in shape and magnitude to the SAE cold climate average, except in the 63-Hz 1/3-octave band.

For purposes of further comparison to data obtained in colder climates, the average results from the literature for eighteen rooms in 6 houses in Boston and New York [27] are presented in Fig. 16 along with the average results of the present study. Also indicated in Fig. 16 is the range of values observed in the Boston and New York data. This range, about 9 to 17 dB, is similar to the range in NIR values observed in the current study, as shown in Fig. 14. The shape and magnitude of the two average building sound isolation spectra presented in Fig. 16 are also similar.

Although most of the building sound isolation data reported in the literature are octave band spectra, the results of one study are presented as average 1/3-octave band values for two houses [17]. These data are presented in Fig. 17 along with the 1/3-octave band average NIR values obtained in the current report for nine test houses. The published data were for a frame house with brick veneer and a frame house with wood siding. In comparison to the average NIR values of the current report, it is seen that the published data display a slightly smaller slope.

The published building sound isolation data reported for traffic noise sources are presented in Fig. 18. The published data in this figure correspond to two studies, one conducted on one apartment in New York City [18] and one study conducted on eight residential buildings in New York City, ten in Boston, and eleven in Los Angeles [28]. Comparison of the published building sound isolation values in Fig. 18 with those of this report indicates that the published spectrum shapes are less steeply sloped than those obtained in the current study. The NIR values reported in the current study are greater than the published data for the New York apartment [18] at the middle and high frequencies. Below 250 Hz, the data from the present study tend to be lower than published data; thus the data of the current study show greater slope with frequency.

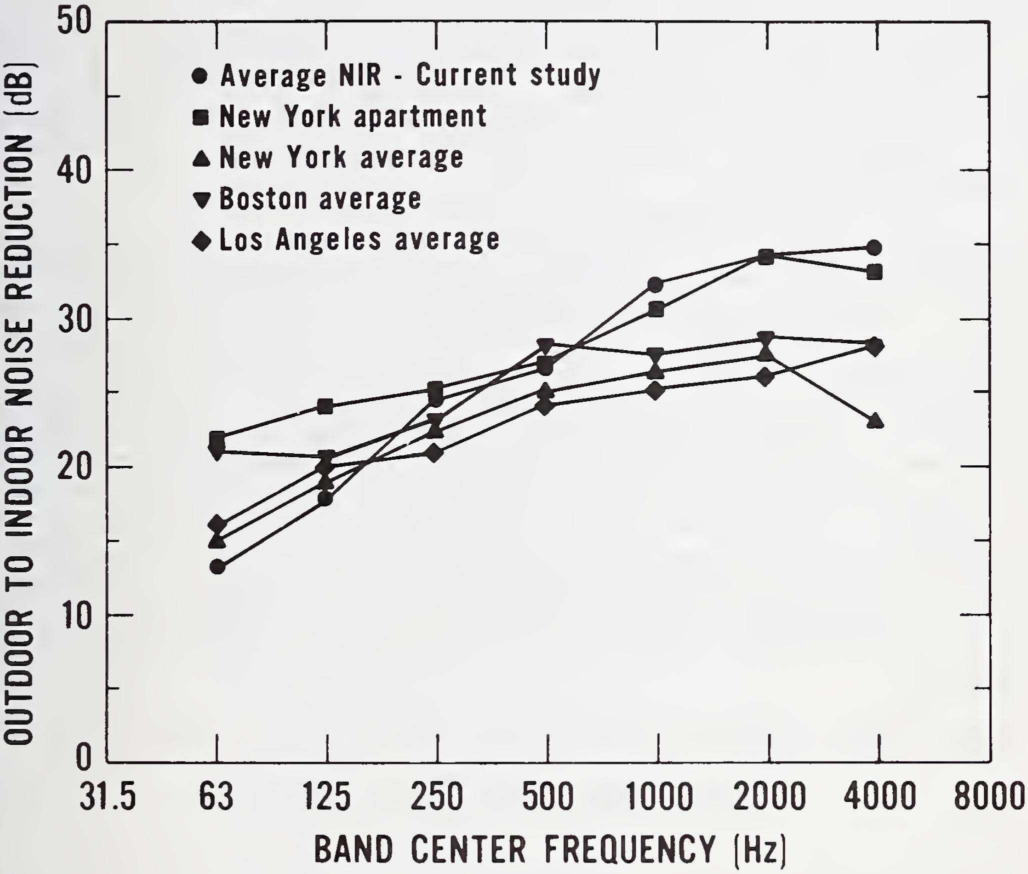

Figure 18. Comparison of average octave-band Noise Intrusion Reduction values from the present investigation with sound isolation values reported in the literature for traffic noise [18,28].

A final comparison of the average sound isolation values from the current study to those reported in the literature is provided in Fig. 19. The published data shown in this figure correspond to building sound isolation data determined for 14 residences in the state of New York [15]. The noise source used in these measurements consisted of three loudspeakers positioned outside the dwelling. The interior sound pressure levels used to calculate attenuation for this study were an average of data from a microphone position at the geometric center of the room and at one typical listener position. Examination of Fig. 19 reveals that the agreement between the published data and those obtained in the current study is good, as indicated by differences of less than 3 dB. Also shown is the range of values obtained in the reported study for the 14 residences. This range, 10 to 17 dB, is similar to that observed in the current study.

From the comparisons in Figs. 15 through 19, it is seen that the sound isolation spectra determined in the current study are similar in both shape and magnitude to most of those reported in the literature for dwellings in cold climates. Further, from those studies in which the observed ranges of sound isolation were reported, it is seen that the range of values in the current study is consistent with ranges reported in the literature. It should be noted, however, that the reported data for dwellings in warm climates tend to have smaller slopes (versus frequency) than those of the current study. For this reason, it should be realized that the filter shape developed as a result of the NIR data obtained in this study is most representative of cold climate dwellings. Because sound isolation spectra for cold climates are more steeply sloped than those for warm climates, use of the cold climate data to derive an outdoor-indoor filter results in a more significant modification of an outdoor spectrum than might be expected to occur in the case of a warm climate dwelling.

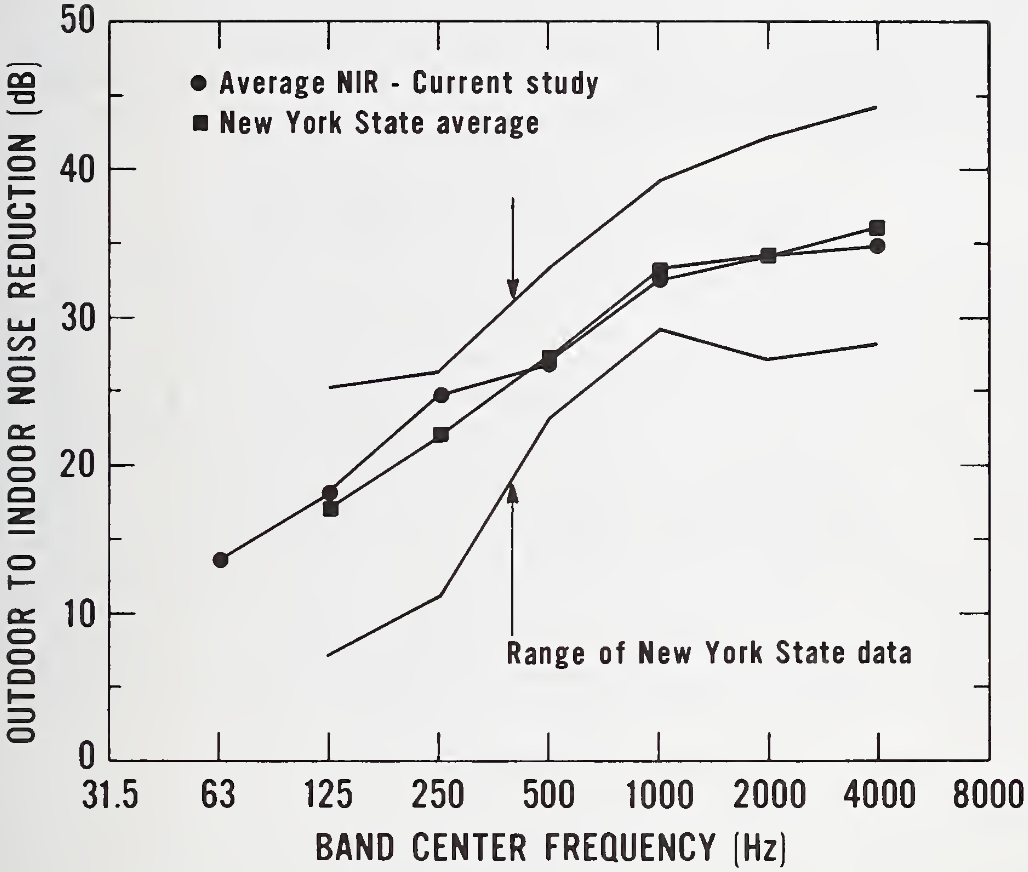

Figure 19. Comparison of average octave-band Noise Intrusion Reduction values from the present investigation with the average and range of sound isolation values reported in the literature for New York state houses subjected to controlled loudspeaker noise sources [15].

5. Discussion of Noise Intrusion Reduction Results

Based on the Noise Intrusion Reduction (NIR) values reported in Appendix C for Data Set No. 2 (see Section 3.3), several aspects of the results obtained in the current study can be considered. These include the dependence of NIR on building facade construction, openings in the facade structure, the position of the exterior sound source, and the microphone positions. The influence of the ratio of facade area to floor area was not considered because of the limited range of this quantity for most of the test houses. Although the data set is restricted to a limited number of houses and pass-bys, the results are believed to be useful in indicating trends which may be more universally valid. These trends should be further investigated.

5.1 Dependence of NIR on Building Facade Parameters

In order to assess, within the current data set, the dependence of NIR on building facade parameters, spatial-average NIR values for individual test houses were grouped according to various facade parameters. For each grouping, NIR values within that group were averaged using Eq. (7). Using the averages and ranges of NIR within each group, comparisons among groupings were made. Groupings were made to enable comparison among the parameters of window type, window area (both frontal and total for the test room), and facade composition. Each grouping consisted of three test houses, selected on the basis of similarity of one facade parameter, for example, all wood-frame exterior wall construction. Due to the limited size of the data set, it should be realized that for a pair of groupings used for a particular comparison, the other facade parameters are varied. Thus, for example, in comparing groupings with and without storm windows present, houses with various wall constructions will be contained within each group. For this reason, specific facade parameters cannot be isolated within each grouping.

5.1.1 Dependence on Presence of Storm Windows

The average NIR values for two groupings of houses with and without storm windows are presented in Fig. 20. Examination of this figure indicates that at frequencies higher than 250 Hz, the average NIR for the group with storm windows is consistently higher than the average for the group without storm windows. Above this frequency, the difference in the average NIR values is 3 to 5 dB, depending upon frequency. In addition to the average of the storm window grouping being higher above 250 Hz, the average of this grouping does not lie within the range of the group without storm windows. Also, the average, above 250 Hz, of the group without storm windows does not lie within the range of the group with storm windows. From Fig. 20 it appears that the presence of storm windows on a building facade typically increases the NIR of a house above 250 Hz.

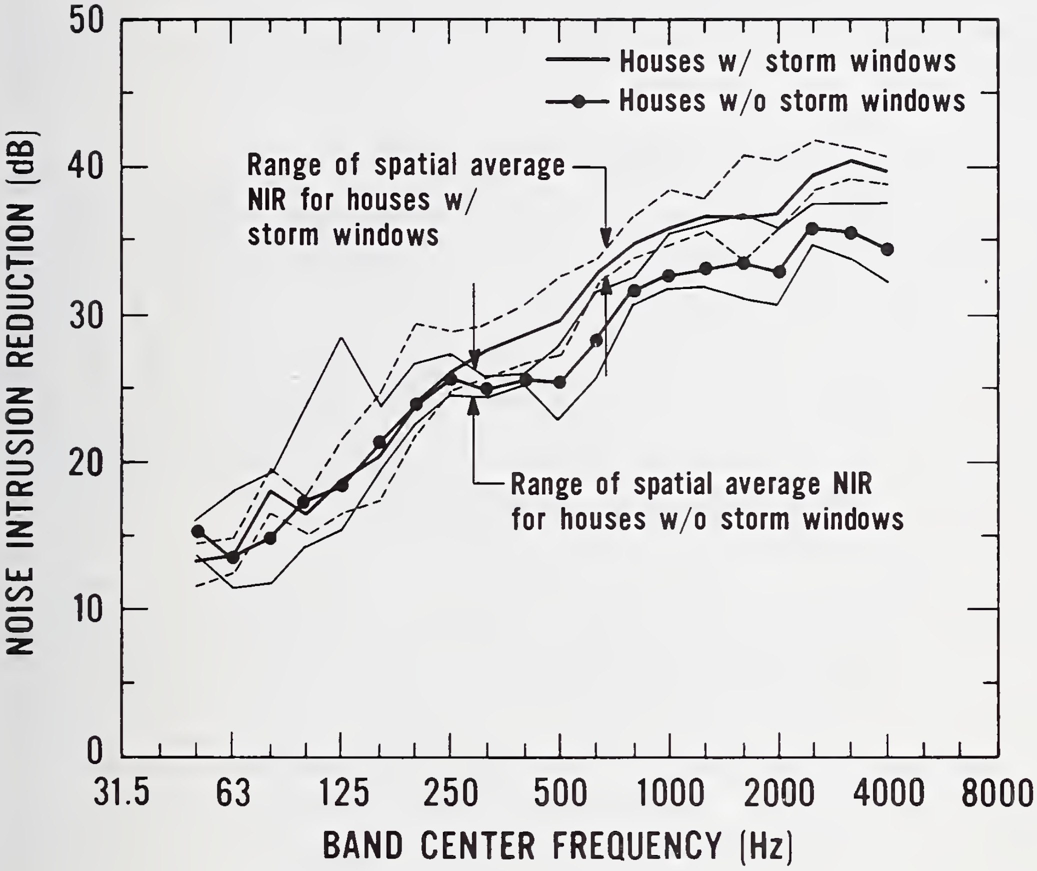

Figure 20. Comparison of Noise Intrusion Reduction values averaged for houses with and without storm windows.

The behavior indicated in Fig. 20 is consistent with findings from laboratory tests of exterior window configurations. These laboratory data show increased sound transmission loss when storm windows are added to existing single windows (e.g., see [29]). Further, from previous studies, it is known that transmission through windows is the path which typically controls the overall sound insulation of a building facade at higher frequencies [7,26]. For these reasons, the increase in measured NIR indicated in Fig. 20 for houses with storm windows is generally consistent with expectations based upon laboratory data.

5.1.2 Dependence on Window Area

Within the set of nine test houses in the current study, the range of frontal window areas was from 2.3 to 4.5 m^2, as indicated in Table 1. To facilitate comparison of NIR values on the basis of frontal window area, the three houses with the smallest areas (2.3, 2.7, and 3.3 m^2) were grouped together to form the first group and the three houses with the largest areas (3.6, 3.9, and 4.5 m^2) were grouped together to form the second group. The NIR averages and ranges of these groupings are presented in Fig. 21. This figure indicates that there is no discernible difference between the two groupings. The curves defined by the average values of groups display considerable crossing of each other throughout the frequency range and the range of values for each group consistently overlap.

Although there is no observable difference between the two groupings of Fig. 21, the sound transmission loss of facades is dependent on window area with sound transmission loss decreasing with increasing window area [26,29]. However, for this effect to be pronounced, the change in the ratio of window area to wall area must be significant. For example, a change in the window-to-wall area from a ratio of 10 percent to a ratio of 40 percent typically produces at most a 5.5 dB decrease in the sound transmission loss of a composite exterior wall [26]. For the average NIR values shown in Fig. 21, the difference in the average window areas between the two window area groupings is only 1.2 m^2 for total wall areas of about 15 m^2. With such a small change in window-to-wall area ratios, the similarity between the two groupings of Fig. 21 is expected, particularly since the influence of window type can be expected to overwhelm the influence of window area for the houses of the present study.

In addition to comparing groupings of test houses on the basis of frontal window area, a comparison was made on the basis of total window area within the test room. In producing the groupings for this comparison, however, the group with the larger total window area (4.6, 5.0, and 5.5 m^2) was comprised of three test houses with test-room windows to the side of the house, while only one such house was included in the group with smaller total window area (3.3, 3.4, and 3.8 m^2). Because of this difference in the location of windows relative to the noise source, the resultant comparison must be qualified. The averages and ranges of NIR for the two groupings of total window area are presented in Fig. 22. The values shown in this figure indicate that the average

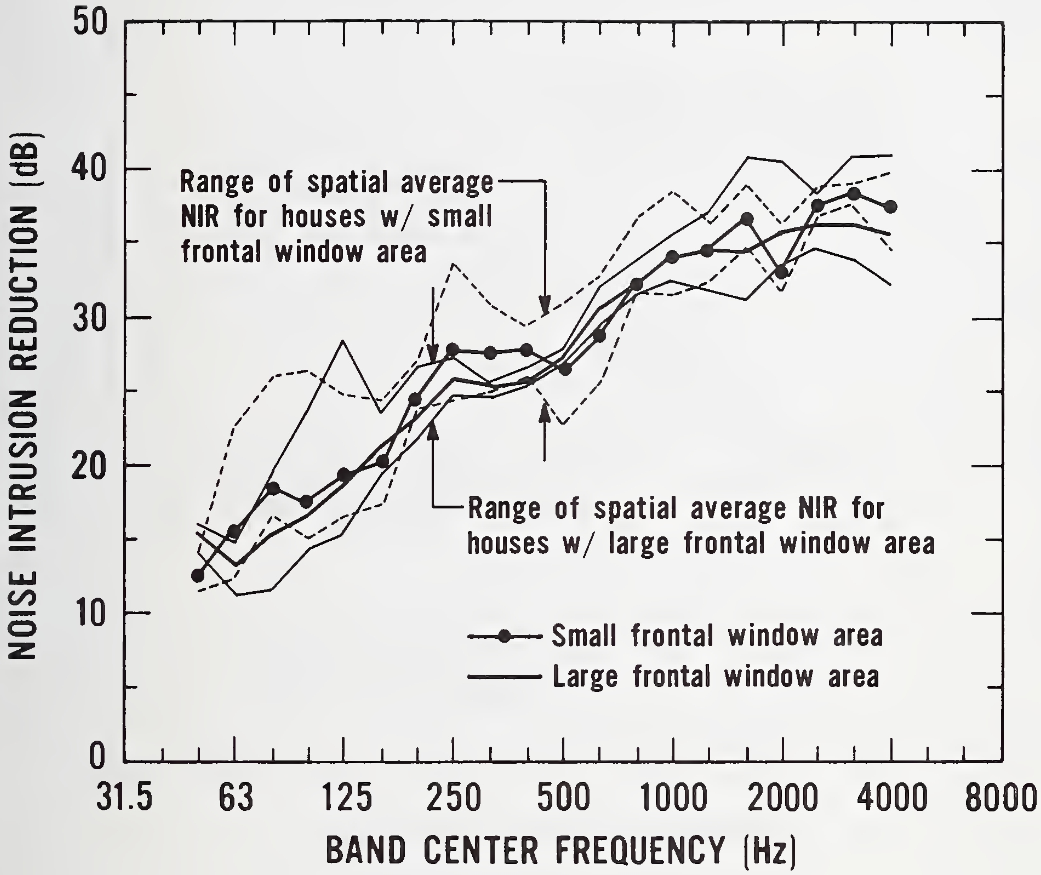

Figure 21. Comparison of Noise Intrusion Reduction values averaged for houses with large and small frontal window areas.

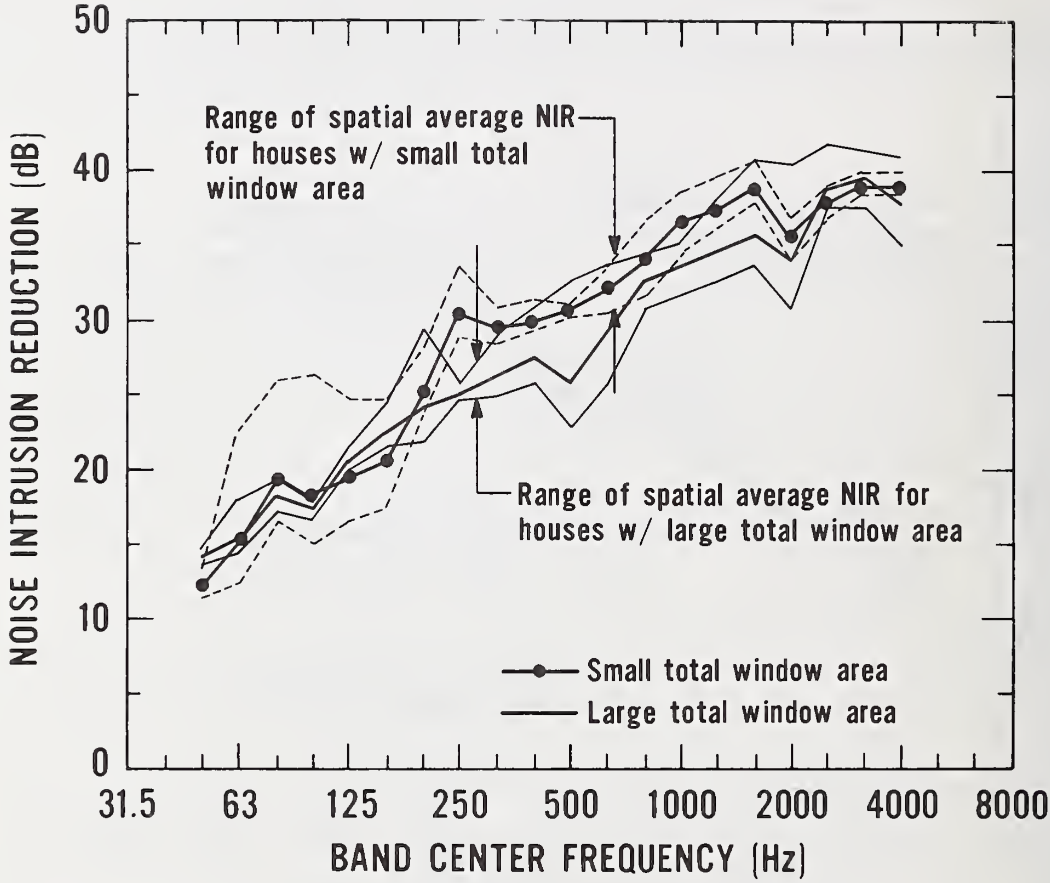

Figure 22. Comparison of Noise Intrusion Reduction values averaged for houses with large and small total window areas.

NIR of the group with smaller total window area is consistently larger than the average NIR for the group with larger window area for frequencies ranging from 250 to 2,000 Hz. The significance of this average difference is inconclusive as the average of the smaller total window area group is contained within the range of the larger window area group for seven of the ten 1/3-octave bands from 250 to 2,000 Hz. Little difference in the group NIR averages in Fig. 22 is expected as the increase in window-to-wall area ratio is small between the groupings.

5.1.3 Dependence on Facade Wall Composition

Although all of the test houses were basically of frame construction, the exterior finish varied within the set of nine houses. Two common types of exterior finish were brick veneer (at least to the height of the ceiling of the test room) and wood siding. Three houses of each type were selected to form groupings to enable a comparison of NIR values for the two facade wall compositions. The averages and ranges of NIR for these two groupings are presented in Fig. 23. Examination of this figure reveals that for frequencies from 63 to 500 Hz the average NIR value for the group of houses with brick veneer is consistently higher by 2 to 8 dB than the average for the group of houses with wood siding. It, appears, therefore, that a facade with brick veneer may typically increase NIR at low frequencies relative to that of a house with wood siding.

The increased NIR observed in Fig. 23 for brick veneer exterior walls relative to wood siding is qualitatively consistent with findings reported in the literature. In one laboratory study of the sound transmission loss of exterior walls with windows, the data reproduced in Fig. 24 were obtained [29]. The increased sound transmission loss for brick veneer walls in the 1/3-octave bands from 100 to 200 Hz, relative to that for wood siding walls, is similar to the increase observed for NIR in Fig. 23.

From Figs. 20 to 23 it is observed that if two houses were similar except that one had brick veneer and storm windows and the other had wood siding and no storm windows, then the NIR of the first house would be expected to be higher than the second throughout the entire frequency range. This conclusion is based on the observed increased NIR at high frequencies for facades with storm windows relative to those without and the increased NIR at low frequencies for facades constructed of brick veneer as opposed to wood siding. To verify this observation, it would be desirable to study additional houses. However, lacking additional data, a comparison between Test House No. 7 and No. 8 can be made. These two houses have similar window areas and both have test-room windows to the side of the house. House No. 7 has brick veneer and storm windows while House No. 8 has wood siding and no storm windows. The average NIR for each house is plotted in Fig. 25. As would be expected from the above arguments, the NIR values for House No. 8 are lower than those for House No. 7 by 2 to 7 dB for almost all frequency bands. (Note that the isolation provided by a given house is also dependent upon air leaks as well as upon the wall and window types.)

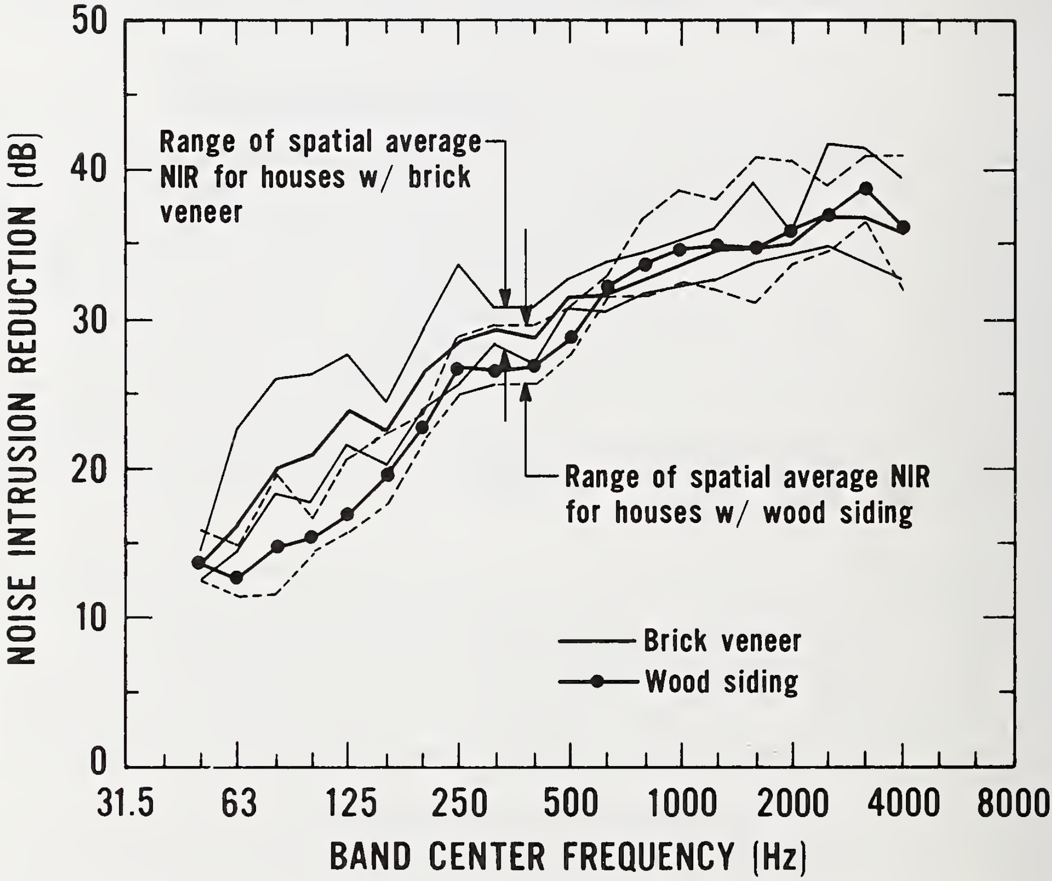

Figure 23. Comparison of Noise Intrusion Reduction values averaged for houses with brick veneer and wood siding.

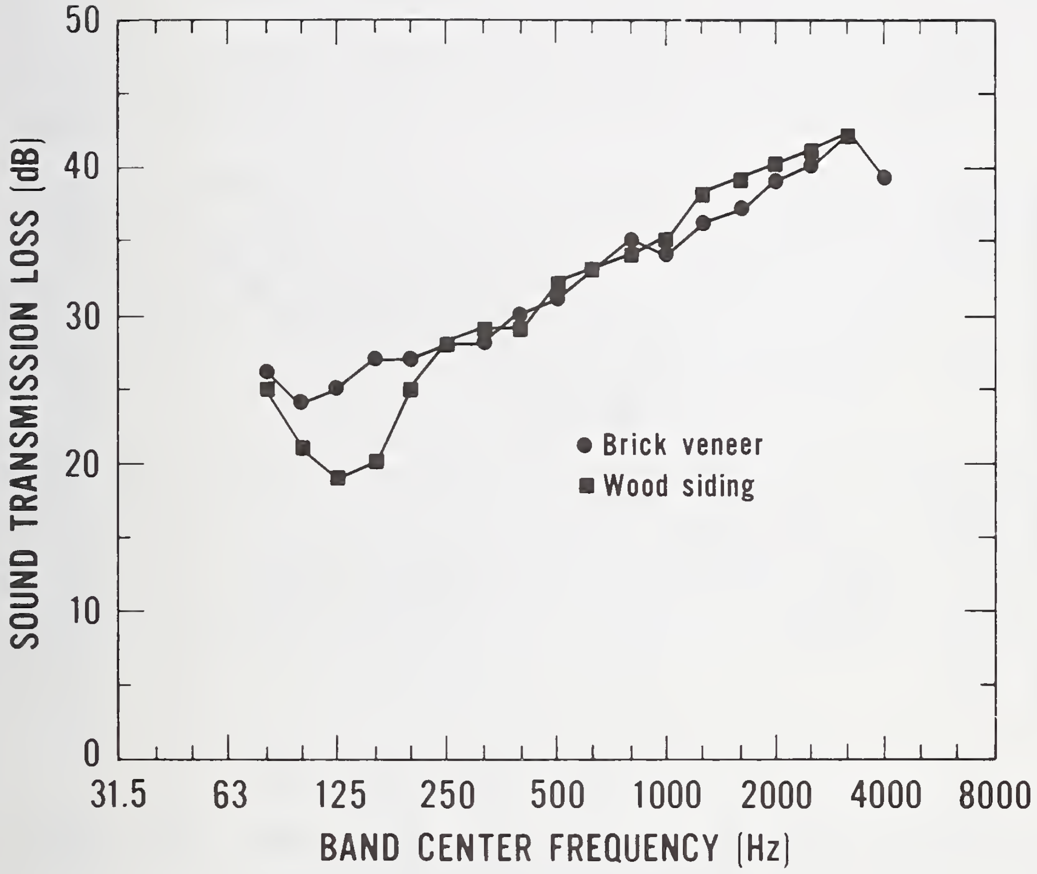

Figure 24. Comparison of published sound transmission loss data for exterior walls with brick veneer and wood siding [29].

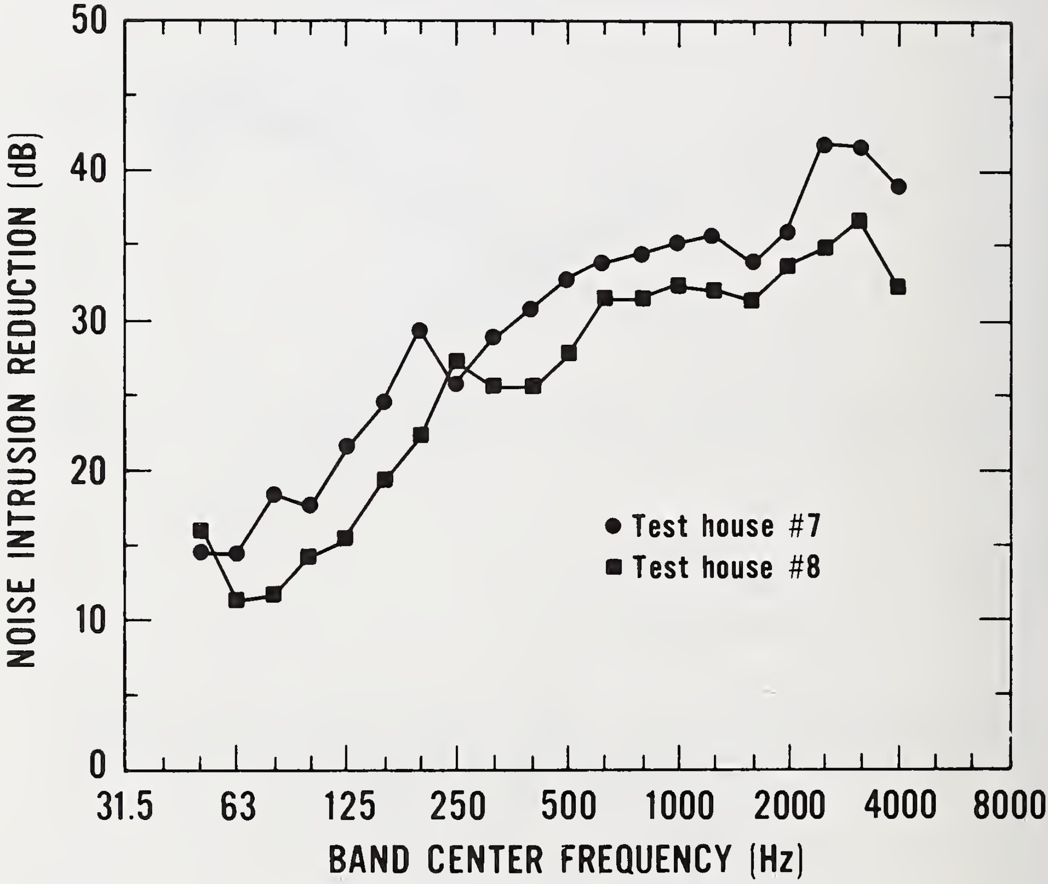

Figure 25. Comparison of Noise Intrusion Reduction values, averaged over listener positions, for Test Houses No. 7 (with brick veneer and storm windows) and No. 8 (with wood siding and no storm windows).

5.2 NIR with Windows or Doors Open

A comparison of the average NIR values with and without exterior windows open for Test House No. 2 is presented in Fig. 26. For this particular case, the total open area of the windows was 0.72 m^2 with the open windows on the front of the house. As would be expected, the effect of opening the windows is to lower the NIR of the building throughout the entire frequency range. The lowering of the average NIR values is particularly pronounced at the middle and high frequencies, above about 80 Hz. Further, the average NIR values display only limited frequency dependence, with all 1/3-octave band values lying between 10.5 and 18.5 dB and with nearly zero slope for the NIR-versus-frequency curve.

The effect of open windows on sound isolation, as indicated in Fig. 26, is consistent with data reported in the literature. Typically, reported values of sound isolation are not significantly dependent on frequency, ranging from 10 to 20 dB for octave bands centered from 63 to 4,000 Hz [8,14,18,30]. Individual differences among the various studies are probably attributable to variables such as window area, source of exterior noise, location of the noise source, and microphone positions.

An effect similar to that illustrated in Fig. 26 was observed for average NIR values with and without an exterior door open for Test House No. 9, as presented in Fig. 27. For this case, although the front door of the house was open, the storm door on the opening was left in the closed position. The storm door, however, had a 0.54 m^2 screened opening. Except for the 1/3-octave bands centered at 50 and 63 Hz, the resultant average values of NIR are not significantly dependent on frequency, all 1/3-octave band NIR values lying between 12 and 18 dB at frequencies above 63 Hz.

5.3 Dependence of NIR on Exterior Noise Source Position

5.3.1 Exterior Windows Closed

As discussed in Section 3.3, NIR values for Test House No. 8 at five instances during a single passby of that house were obtained for Data Set No. 1. These values were calculated using sound pressure levels (reduced using an integration time of 0.2 seconds) which occurred simultaneously at the exterior and interior microphone positions. The times for which the NIR values were obtained correspond to the time at which the maximum A-weighted sound level occurred at the interior reference microphone position, 2.8 and 1.4 seconds before this maximum, and 1.4 and 2.8 seconds after the maximum. The average NIR values corresponding to these five instances during the passby for House No. 8 are plotted in Fig. 28. Examination of this figure reveals that generally there was no consistent relationship among the NIR values at the different times during the passby. One exception to this generality occurs at frequencies above 630 Hz. In this frequency range,

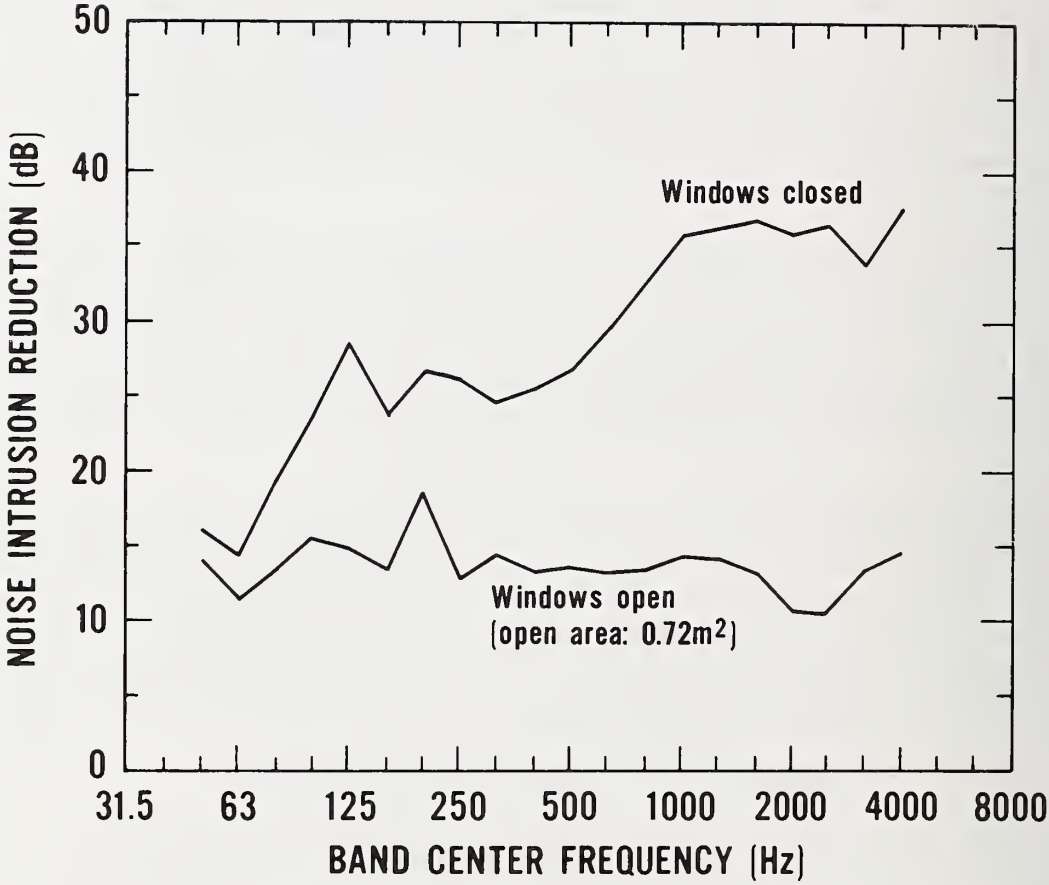

Figure 26. Comparison of Noise Intrusion Reduction values, averaged over listener positions, for Test House No. 2 with and without windows open.

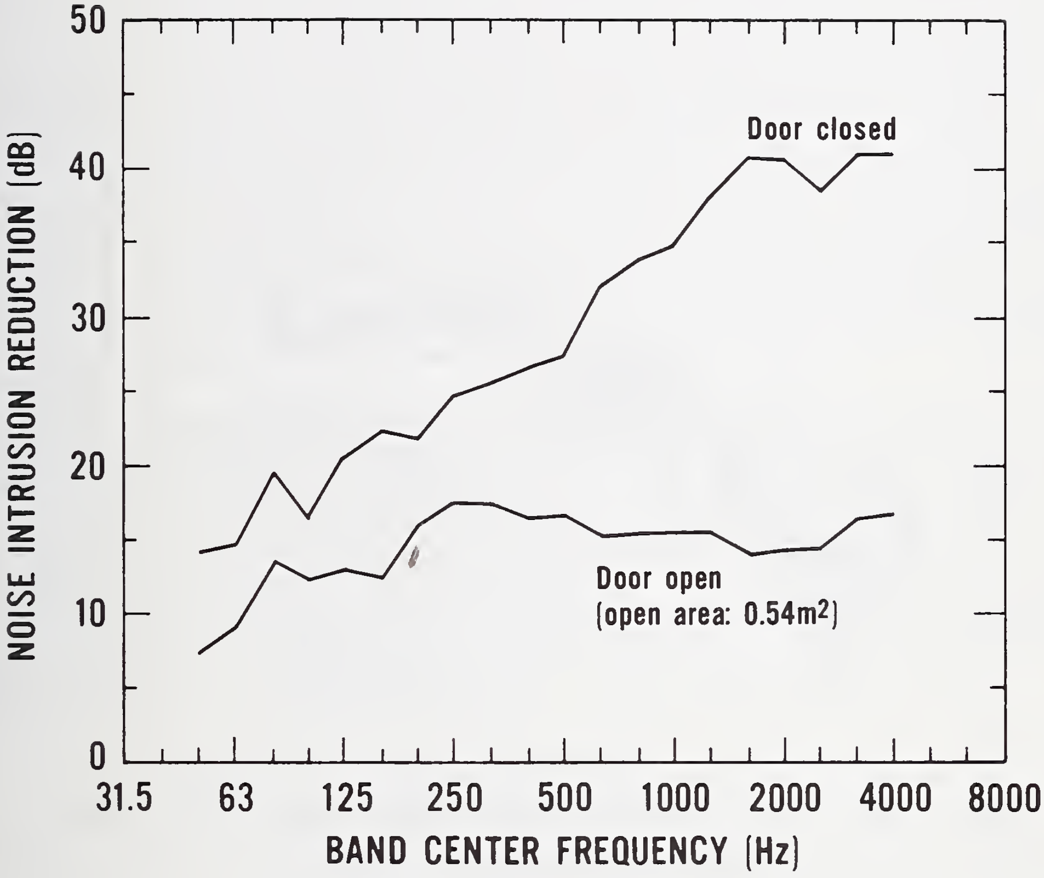

Figure 27. Comparison of Noise Intrusion Reduction values, averaged over listener positions, for Test House No. 9 with and without front door open.

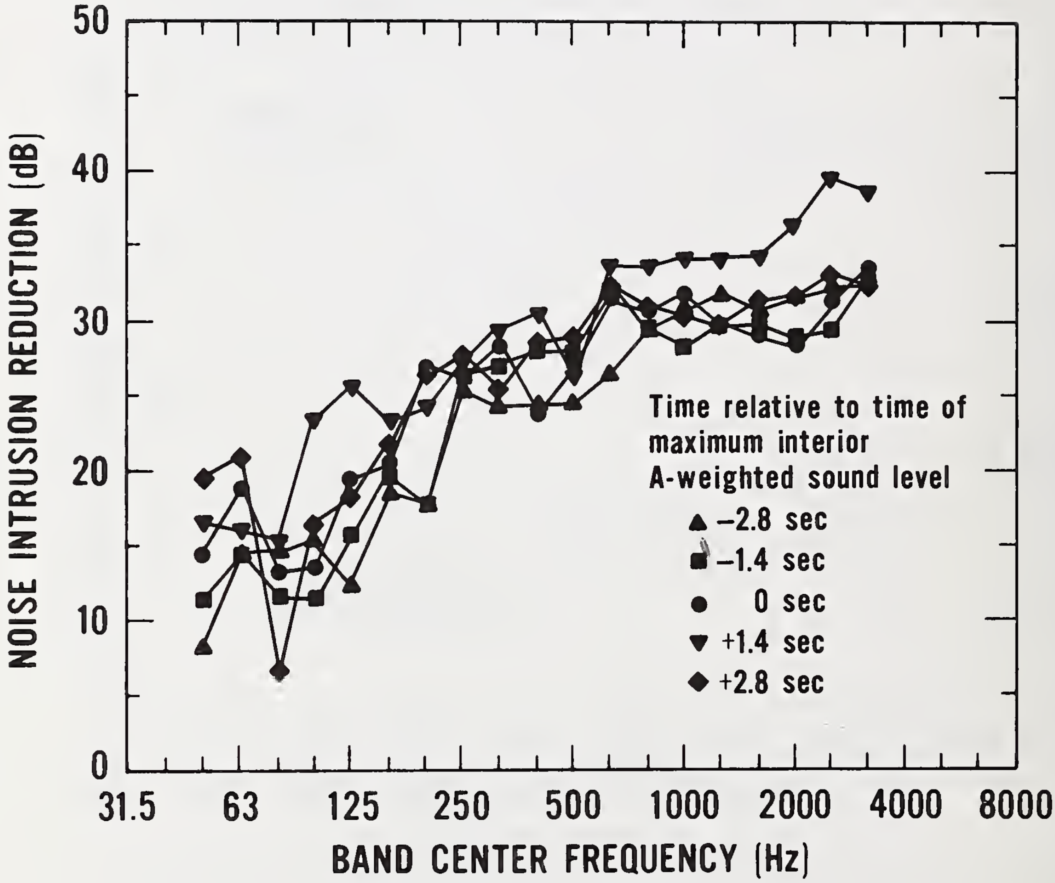

Figure 28. Comparison of Noise Intrusion Reduction Values, averaged over listener positions, at various times during the vehicle passby as determined from simultaneously occurring exterior and interior sound pressure levels at Test House No. 8 with windows closed.

the NIR values corresponding to 1.4 seconds after the maximum interior level are consistently and significantly higher than those values for the other times. This difference between the NIR value at 1.4 seconds after maximum and the other values ranges from 2.5 to 10 dB in the 1/3-octave bands above 630 Hz.

Although the position of the vehicle is not precisely known at the times during the passby shown in Fig. 28 and the temporal variation in outdoor-to-indoor sound level difference also depends upon the directivity of the source, some qualitative inference of the dependence of NIR above 630 Hz on source position can be made from Fig. 28. As the vehicle approaches the house, the NIR values (above 630 Hz) remain relatively low and then at some point when the vehicle is adjacent to the house (i.e, when the sound from the vehicle is at near normal incidence relative to the front facade), the NIR value increases by 2.5 to 10 dB. As the vehicle recedes from the house, the NIR values decrease.

The qualitative behavior of NIR values during the vehicle passby inferred above is generally consistent with the fact that the sound transmission loss of windows decreases as the angle of incident sound increases from normal incidence [23-25]. Although sound transmission loss will vary depending on parameters such as window size, thickness, and double glazing, this basic angular dependence occurs for most window designs [25]. Further, since the sound transmission loss of windows is often the limiting element in the sound insulation capabilities of facade structures [26], it is expected that measures of sound isolation in most field situations will display some angularly-dependent behavior.

5.3.2 Exterior Windows Open

A comparison of NIR values at different instances during the vehicle passby is presented in Fig. 29 for Test House No. 2 with the front windows open. In this case, the NIR values determined with simultaneously occurring exterior and interior sound pressure levels correspond to instances 2.0 seconds before, at, and 2.0 seconds after the time when the maximum A-weighted sound level occurred at the interior reference microphone position.

Although there is variation among the NIR values occurring at the three instances of time during the passby, the relationship among the values at different times is not consistent from one 1/3-octave band to another except in the ranges from 100 to 200 Hz and from 1,000 to 2,500 Hz. In the lower of these two frequency ranges, the values of NIR at near normal sound incidence (i.e., NIR at the time of maximum interior A-weighted sound level) are higher

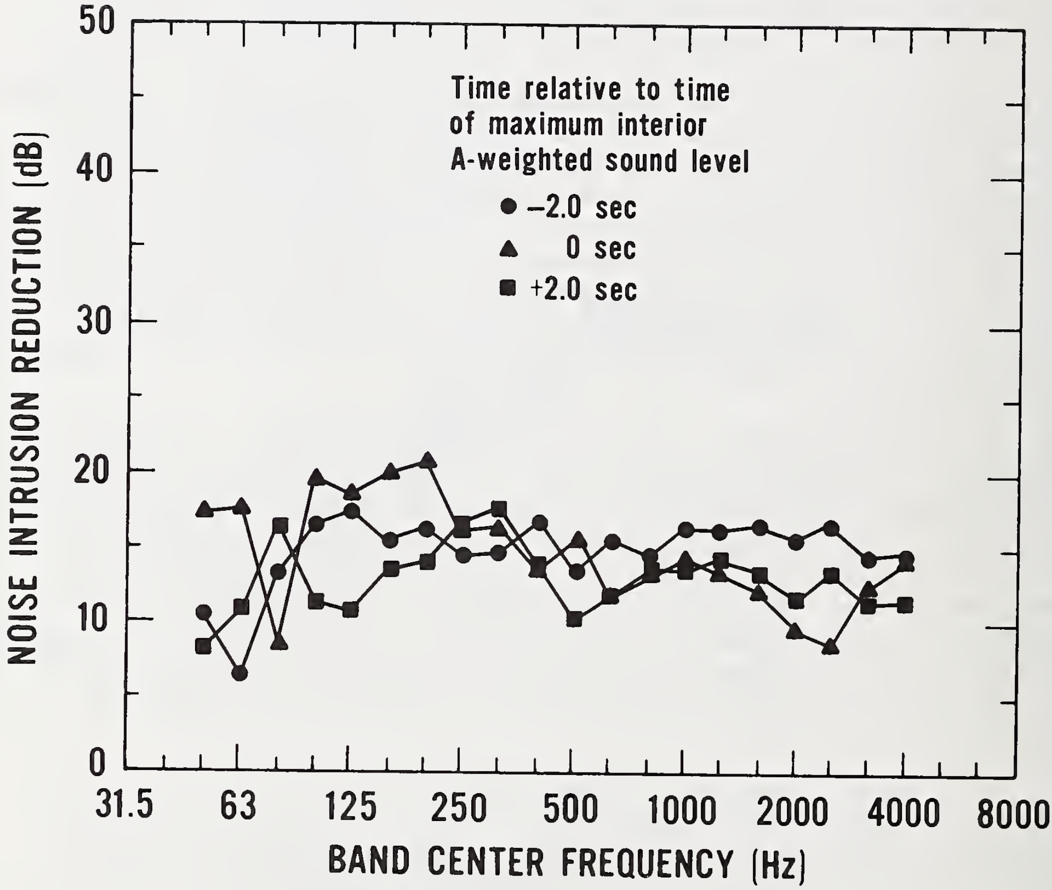

Figure 29. Comparison of Noise Intrusion Reduction Values, averaged over listener positions, at various times during the vehicle passby as determined from simultaneously occurring exterior and interior sound pressure levels at Test House No. 2 with windows open.

than the values before and after the maximum. In the higher frequency range, this ordering is reversed as the NIR values at near normal incidence are less than the other two. It should be further noted that in the higher of these frequency ranges, the qualitative behavior of NIR values during the vehicle passby with the windows open is the opposite of that observed with the windows closed. With the windows open, the NIR decreases as the vehicle approaches the house, reaching a minimum when it is in front of the house (near normal incidence) and then increasing again as the vehicle continues on beyond the house. This behavior is consistent with that reported in the previous work for the high frequency case when the acoustic wavelength of the incident sound is less than the dimensions of the window opening. For this high frequency case, the sound transmission loss of an open window increases with increasing angle of incidence as $\ell og(\sec \theta)$, where θ is the angle from normal incidence [24].

5.4 Variation Between NIR Values for Listener and Interior Reference Microphone Postions

The NIR values reported in Appendix C (Data Set No. 2 of Sec. 3.3) for one vehicle passby at each of the nine test houses can be used to make some comparison between NIR values determined at individual listener positions and the interior reference microphone position. As noted in Sec. 3.2, at each of the nine test houses the interior reference microphone was 1 m from one of the test room windows which faced the street on which the vehicle passed by. On the other hand, the listener position microphones bore no particular relationship between one house and the next as they were determined by the location of furnishings in each individual room. Due to the consistency of the placement of the reference microphone position, it is of interest to compare the NIR values measured at this position with those determined at the listener positions to determine if any consistent relationship exists from house to house.

To compare reference and listener position NIR values, the NIR value determined at the reference microphone position for each house was subtracted from each of the three individual listener position NIR values for the corresponding house. With the nine test houses, 27 such differences between listener and reference position values were obtained for each 1/3-octave band centered from 50 to 4000 Hz. The mean ($\bar{x}$), standard deviation (σ), and extremes of the 27 values in each 1/3-octave band were then determined. These resultant values are plotted in Fig. 30 and are presented in Table 4. To provide some indication of the distribution of the values of difference between the listener and reference positions, frequency histograms of these values are presented in Fig. 31 for the 1/3-octave bands centered at 125, 500, and 2500 Hz.

Prior to examining the results presented in Fig. 30 and Table 4, the distributions indicated in the frequency histograms of Fig. 31 should be considered. From this figure, it appears that the distributions of the NIR differences tend to approach a normal distribution for the 500- and 2500-Hz 1/3-octave bands. For the 125-Hz 1/3-octave band data, however, a tendency toward normal distribution is less apparent. More data would be required to ascertain the form of the distribution for the 125-Hz band.

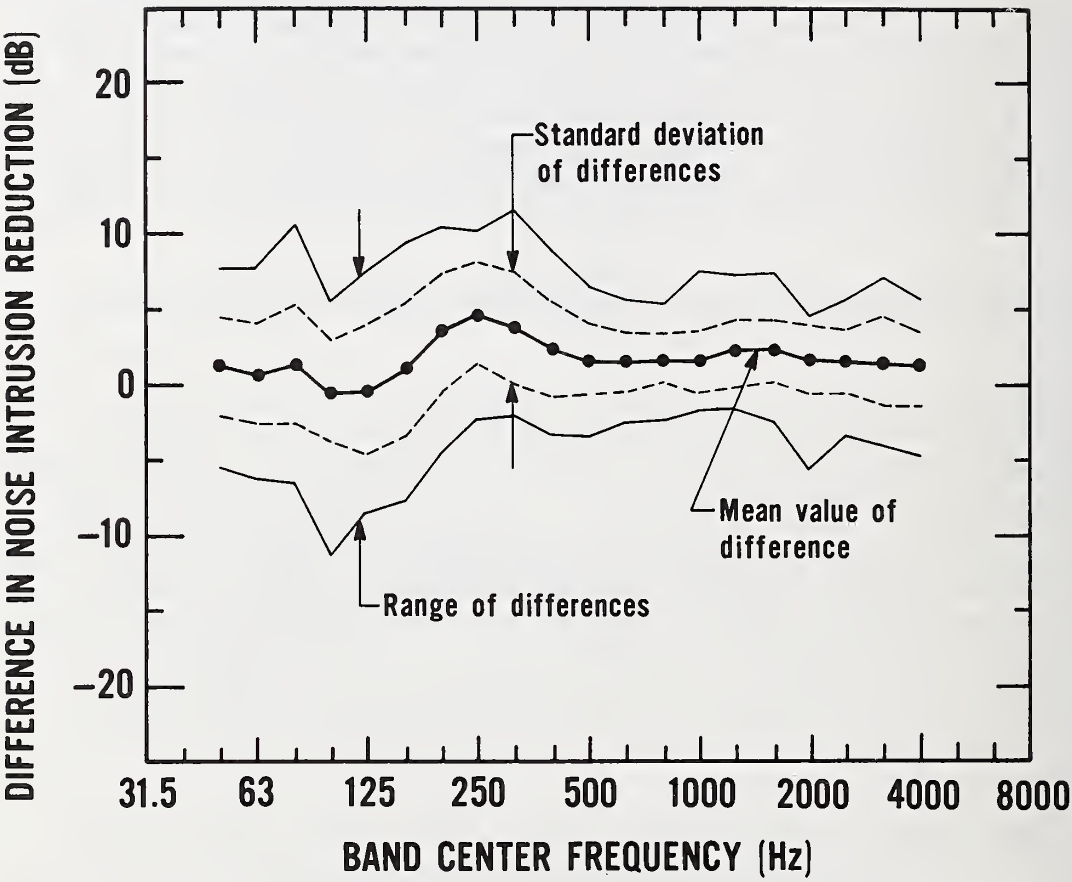

Figure 30. Mean, standard deviation, and range of differences between Noise Intrusion Reduction values determined for individual listener positions and those for interior reference positions, for the set of all nine test houses.

Table 4. Mean, standard deviation, and extreme values of differences between NIR values determined at individual listener positions and at interior reference positions for all nine test houses.

1/3-Octave Band Center Frequency	Difference Between NIR Values for Listener and Reference Positions			
	Mean	Standard Deviation	Maximum	Minimum
50 Hz	1.3 dB	3.3 dB	7.9 dB	- 5.3 dB
63	0.8	3.3	7.9	- 6.1
80	1.4	3.9	10.7	- 6.4
100	-0.4	3.4	5.6	-11.1
125	-0.3	4.3	7.6	- 8.3
160	1.1	4.3	9.7	- 7.6
200	3.6	3.8	10.5	- 4.4
250	4.8	3.3	10.2	- 2.2
315	3.9	3.8	11.7	- 2.0
400	2.4	3.2	8.9	- 3.1
500	1.7	2.3	6.5	- 3.3
630	1.6	1.8	5.8	- 2.3
800	1.8	1.7	5.4	- 2.1
1000	1.7	2.1	7.6	- 1.7
1250	2.1	2.2	7.2	- 1.6
1600	2.3	2.1	7.5	- 2.2
2000	1.8	2.3	4.8	- 5.6
2500	1.7	2.1	5.8	- 3.1
3150	1.5	2.8	7.1	- 4.0
4000	1.2	2.4	5.8	- 4.8

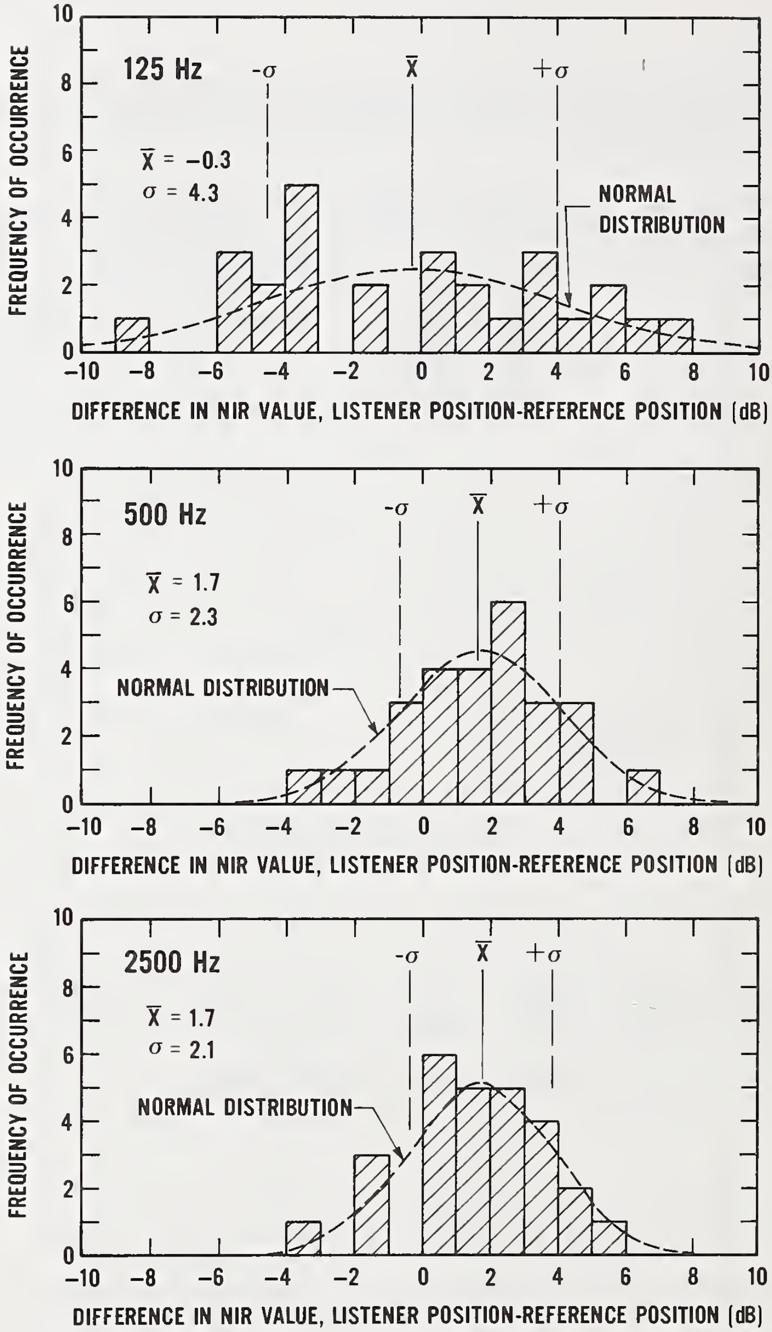

Figure 31. Frequency histograms of the differences between Noise Intrusion Reduction values determined at individual listener positions and at the interior reference position for all nine test houses.

Examination of the data in Fig. 30 and Table 4 reveals that, except for the two 1/3-octave bands centered at 100 and 125 Hz, the mean values of the difference in NIR values are consistently positive. This indicates that, on the average, the NIR values for the listener positions are higher than those for the reference position. Above 315 Hz, the mean difference is between +1 and +3 dB; from 200 to 315 Hz, the mean is slightly higher, +3 to +5 dB; below 200 Hz, the mean varies from about -.5 to +1.5 dB. Although the frequency dependence of the mean values appears to have some consistency, further data and analyses would be required to provide quantitative explanations of the observed behavior. The standard deviations and ranges of values also indicate some frequency dependence, with these quantities generally decreasing with increasing frequency. This behavior is consistent with the higher spatial variation of NIR values that is evident in the lower frequency bands.

The standard deviations in Fig. 30 and Table 4 range from 1.7 to 4.3 dB. The range of values varies from 7.5 to 17.1 dB. From Fig. 30 and Table 4, the NIR values at listener positions can be estimated from measured values obtained at the reference microphone position. In field measurement situations, if resources preclude the use of more than one microphone, the reference microphone position could be used with the data of Fig. 30 and Table 4 used to estimate NIR values at listener positions.

6. Implication of Results for Measurements of Sound Isolation

6.1 Measurements of Exterior Sound Pressure Levels

6.1.1 Theoretical Considerations

As discussed in Sec. 2.2.1, the sound incident on a building facade is measured in the presence of the vertical surface defined by the facade. The presence of this vertical surface creates ambiguity in the determination of the magnitude of the incident sound as the sound pressure level measured adjacent to the building results from a combination of directly incident and reflected sound. Because of interference between the direct and reflected sound, frequency dependent differences between measured sound pressure level and the level of the incident sound wave occur as a function of the distance of the microphone from the surface and of the characteristics of the surface. For this reason, in determining building sound isolation or facade insulation, the influence of the placement of the exterior microphone relative to the building facade is important.

In order to obtain a basic understanding of the variations in the sound pressure level occurring as a result of interference between the direct and reflected sound waves caused by the vertical plane of the building surface, a simple model of the building surface is of use. In previous studies of sound reflection [33] it has been assumed that the vertical building surface is planar, infinite in extent, and of real acoustic impedance and that reflections from this surface are specular. To illustrate the application of this model to building surfaces, a value of acoustic impedance corresponding to a normal incidence sound absorption coefficient of 0.1 can be assumed. This value of sound absorption is typical of exterior building materials such as brick, concrete, wood, and glass over the frequency range of interest [34].

Using the above model, the increase in 1/3-octave band sound pressure level, due to reflected sound, above the level of the incident sound, can be calculated [33]. The increase in level for normally incident sound is plotted in Fig. 32 as a function of path length difference between the sound arriving directly from the noise source to the microphone position and that which is reflected from the vertical building surface. The path length difference in Fig. 32 is expressed in terms of acoustic wavelengths since the increase in level due to reflection is both a function of path length difference and acoustic wavelength (or alternatively, frequency). In calculating the values shown in Fig. 32, the direct path of sound from source to receiver was taken to be much greater than the path length difference between direct and reflected sound in order to eliminate dependence of increased level on the direct path length.

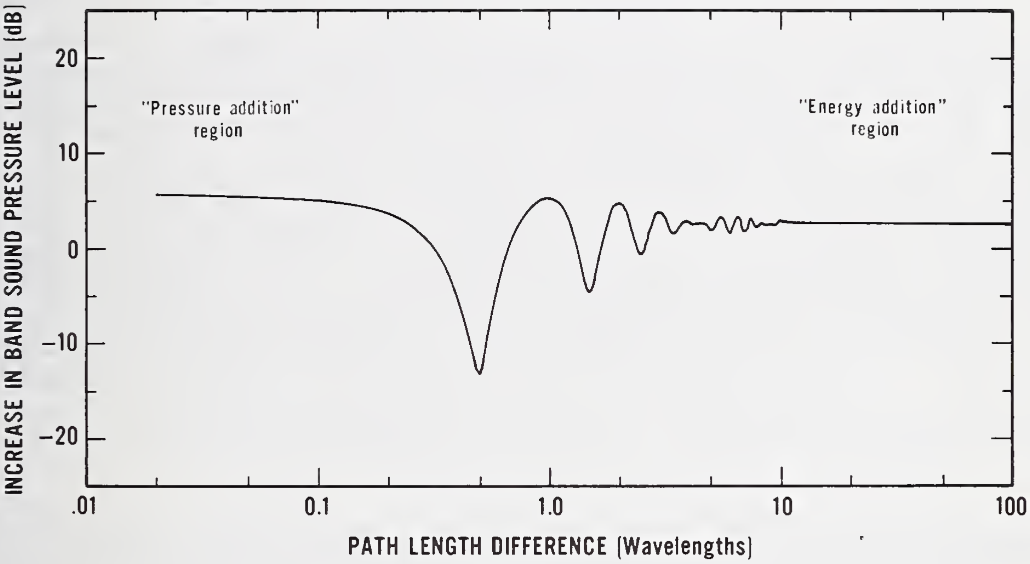

Figure 32. Increase in 1/3-octave band sound pressure level due to reflection from an infinite plane of real impedance with a sound absorption coefficient of 0.1.

From Fig. 32, it is seen that the increase in level due to the sound reflected from a vertical building surface, as idealized above, exhibits variation as a function of path length difference. This variation is most pronounced for path length differences between 0.2 and 4.0 acoustic wavelengths. In this region, minima occur at path length differences of 0.5, 1.5, and 2.5 acoustic wavelengths, corresponding to increased levels of -13, -5, and -1 dB, respectively. Below about 0.2 acoustic wavelengths, the increase in level is essentially independent of path length difference, having a value of about 5.5 dB for the assumed value of 0.1 for the absorption coefficient. This region is commonly referred to as the region of "pressure addition" of the direct and reflected sounds. Above about 4.0 acoustic wavelengths, the increase in level is also virtually independent of path length difference and has a value of about 2.5 dB. This region is commonly referred to as the region of "energy addition" of the direct and reflected sounds.

The information conveyed in Fig.32 can be used to address the question of microphone placement relative to a vertical building surface for the purpose of determining sound isolation. It is seen that if the exterior microphone is placed at a distance such that, for the frequency range of interest, the path length difference is between 0.2 and 4.0 acoustic wavelengths, then the measured exterior 1/3-octave band sound pressure level will be frequency dependent due to the presence of the vertical building surface. However, the distance of the microphone from the building surface can be selected to avoid such frequency dependence. This is accomplished by selecting a distance such that the path length differences, for the frequency range of interest, are contained either in the pressure addition or energy addition region. For these regions the presence of the vertical building surface raises the sound pressure level by nominally 5.5 or 2.5 dB, respectively, assuming an absorption coefficient for the building facade of 0.1.

In practical measurement situations, neither pressure nor energy addition of the direct and reflected sound can be completely achieved for several reasons. For the frequencies of interest, to obtain energy addition for the entire frequency range would require quite large distances from the building surface, e.g., 6-10 m. This would probably be an unacceptably large distance in most measurement situations due to the uncertainty introduced by propagation differences between the microphone position and the building surface and, for traffic noise, due to the fact that the microphones might have to be located in the middle of the street. In addition, the finite extent of buildings and the presence of surface irregularities would lead to departures from the behavior predicted by a simple model based on specular reflection from an infinite vertical plane. To obtain pressure addition for the entire frequency range typically of interest, the microphone would have to be either flush mounted in the building surface or within less than 2 cm of the surface. It should be noted that 2 cm is about the diameter of microphones typically used to make outdoor sound pressure level measurements. Further, this distance would not allow the use of conventional microphone windscreens, which are typically 9 cm or more in diameter. Because

of practical limitations on the use of sufficiently distant or sufficiently close microphone positions relative to the building surface, significant frequency-dependent variations in the measured sound pressure level due to the presence of the vertical building surface will typically occur.

For the energy addition region defined from Fig. 32, reflections from real building surfaces are further modified from the idealization in this figure by scattering from irregularities in the building surface due to window recesses, decorative facade structure, etc. Reflection from surfaces containing variations similar to those typically occurring on building surfaces has been studied both theoretically and experimentally [33,35]. In one study [33], it was determined that the ratio of reflected to incident mean-square sound pressure is dependent on the angle of the incident sound. This was found to be true for octave bands centered from 250 to 2000 Hz. The angular dependence reported in Ref. 33 for typical building surfaces containing periodic irregularities is given in Fig. 33 as averaged over the four octave bands used in the study. From Fig. 33 it is seen that the mean-squared pressure ratio of reflected to incident sound varies from .8 at normal incidence to .2 at grazing incidence. This corresponds to a sound pressure level variation ranging from 2.5 dB to 0.8 dB. In practical situations, the behavior indicated in Fig. 33 increases the uncertainty in the measurement of the exterior sound pressure level by as much as 1.3 dB for the octave bands centered between 250 and 2,000 Hz and for buildings with periodic surface irregularities. For buildings with non-periodic surface irregularities and at frequencies outside the range from 250 to 2,000 Hz, the possible magnitude of this effect is not known at present.

In addition to the dependence of the ratio of mean-squared pressure of reflected and direct sound on angle of incidence as indicated in Fig. 33, it was further reported in Ref. 33 that spatial variation of the reflection ratio occurred depending on the specific details of the surface geometry. An example of such spatial variation is presented in Fig. 34 for one of the surface configurations included in the study for the 500-Hz octave band. In this figure, the specific surface geometry is indicated along with the position of the microphone relative to the surface. The resultant increase in the measured sound pressure level at the microphone position due to the reflected sound is shown as a function of microphone location. For the example of Fig. 34, the measured level varied by as much as 2-4 dB, depending on the exact relation of the microphone position to the building surface. Similar variations were noted for the 250, 1000, and 2000 Hz octave bands and for other surface geometries. Also, the spatial variation of the increased level due to reflection was found to be most pronounced near normal incidence.

The spatial variation indicated in Fig. 34 is expected to exist in most field measurement situations when exterior sound pressure levels are measured in the presence of a vertical building surface. For a stationary source, as examined in Fig. 34, this spatial variation can introduce uncertainties of about 3 dB in the exterior sound pressure levels when measurements are made in octave bands. For narrower frequency bands, the magnitude of the uncertainty

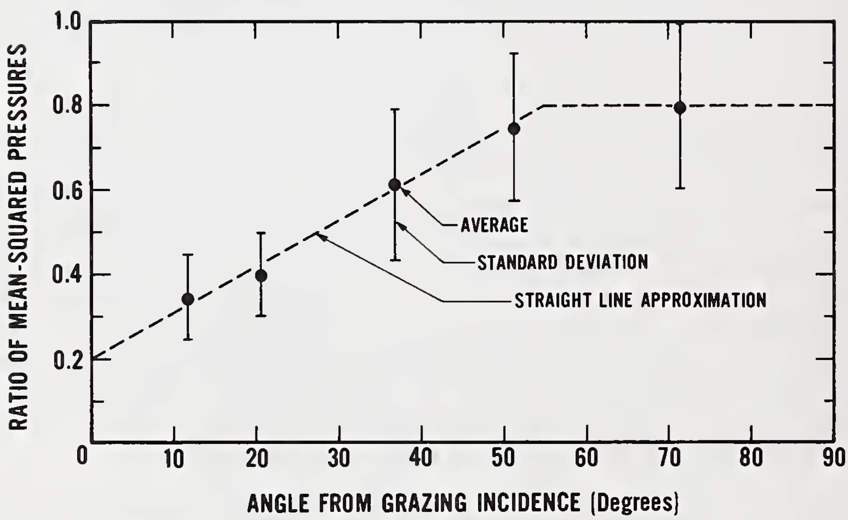

Figure 33. Measured ratio of reflected to incident mean-squared pressures, averaged for frequencies corresponding to 250, 500, 1000, and 2000 Hz [33].

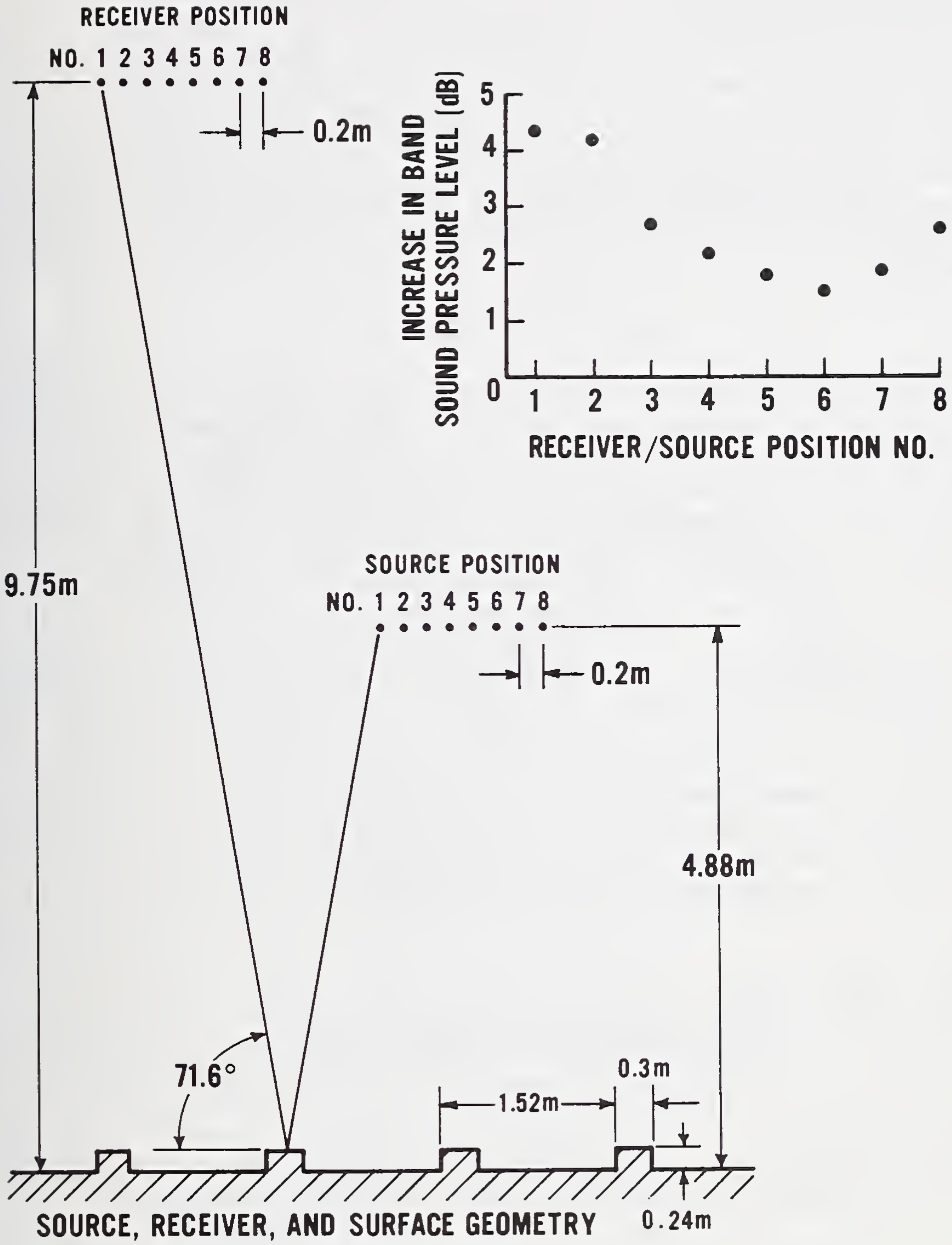

Figure 34. Spatial variation of 500-Hz octave band sound pressure level due to reflection from a periodic, rectangular surface protrusion [33].

has not been determined, but it is expected to be as large or larger than that found when measurements are made in octave bands. Further, it should be noted that if the depths of irregularities in the building surface are less than those indicated in the example of Fig. 34, the indicated spatial variation would still occur, but in a higher frequency band. For example, if instead of being 24 cm, the depth of the protrusions in Fig. 34 was 12 cm, the variation indicated for the 500 Hz octave band would occur in the 1000-Hz band. Thus, even relatively small irregularities in the building surface can produce spatial variation in the measured exterior sound pressure level in some of the frequency bands of interest in measures of building sound isolation.

6.1.2 Results of the Current Study

The measured exterior sound pressure level data obtained in the current study can be used to examine some of the aspects of the exterior measurement problems described in the previous section. As discussed in Section 3.2, three microphones were used to measure outdoor sound pressure level at each test house. Two of these microphones were positioned 3 m away from the building facade and separated by 1.8 m for all nine test houses. The third microphone was positioned 4.5 cm from the facade for seven of the test houses; for the other two houses, one was placed at 15 cm, and one at 1.6 m.

The sound pressure levels measured at the various exterior microphone positions can be used to examine two of the three aspects discussed in the previous section. The data can be used to examine the interference of direct and reflected sound and its relation to microphone placement relative to the building facade. Also, the spatial variation in sound pressure level measured at two microphone positions at 3 m from the building facade can be examined. However, angular dependence of the ratio of reflected to direct mean-square pressure cannot be addressed since the angle of the incident sound is not known and the output of the source was not necessarily constant during the passby.

A comparison between exterior sound pressure levels measured at the three positions for Test House No. 2 is shown in Fig. 35. The sound pressure levels (determined with an integration time of 0.2 seconds) presented in this figure are those which simultaneously occurred at the three positions at the time of maximum A-weighted sound level at the interior reference microphone position. For this house, in addition to the two 3-m exterior positions, a microphone position 4.5 cm from the facade was used.

Much of the variation indicated in Fig. 35 between the sound pressure levels at the 3-m positions and those at the 4.5-cm position can be attributed to differences in interference of the direct and reflected sound for the two microphone distances. The increases in level expected (see Fig. 32) for the two microphone distances of Fig. 35 are presented in Fig. 36 as functions of frequency. From Fig. 36, the differences in the increase in level between the 3-m and 4.5-cm positions indicate that the measured sound pressure levels at the 4.5-cm positions are about 1 to 3 dB higher than those at the 3-m position for frequencies between 50 to 800 Hz, except for the 80 Hz band. This predicted behavior is seen in Fig. 35 for most of these frequencies, particularly those between 250 and 800 Hz. For the 80-Hz band, Fig. 36 indicates that the difference between the levels at the two microphone

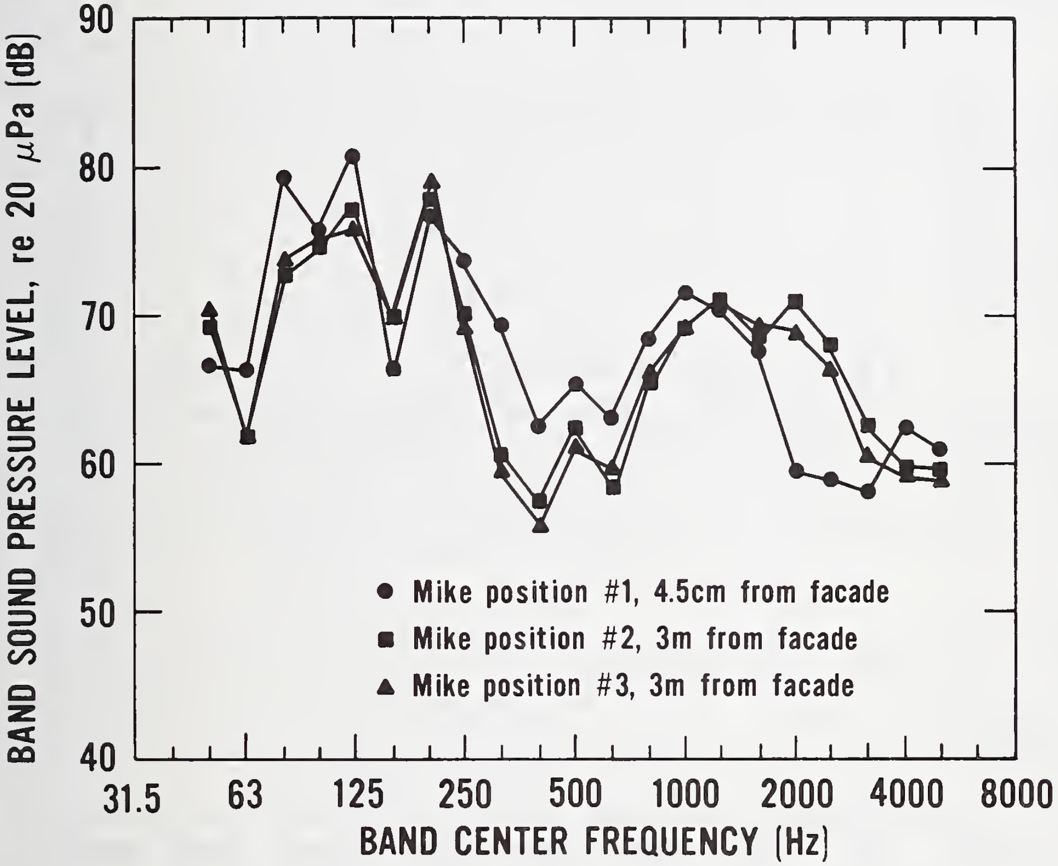

Figure 35. One-third octave band sound pressure levels measured outside Test House No. 2 at three microphone positions at the time of maximum interior A-weighted level.

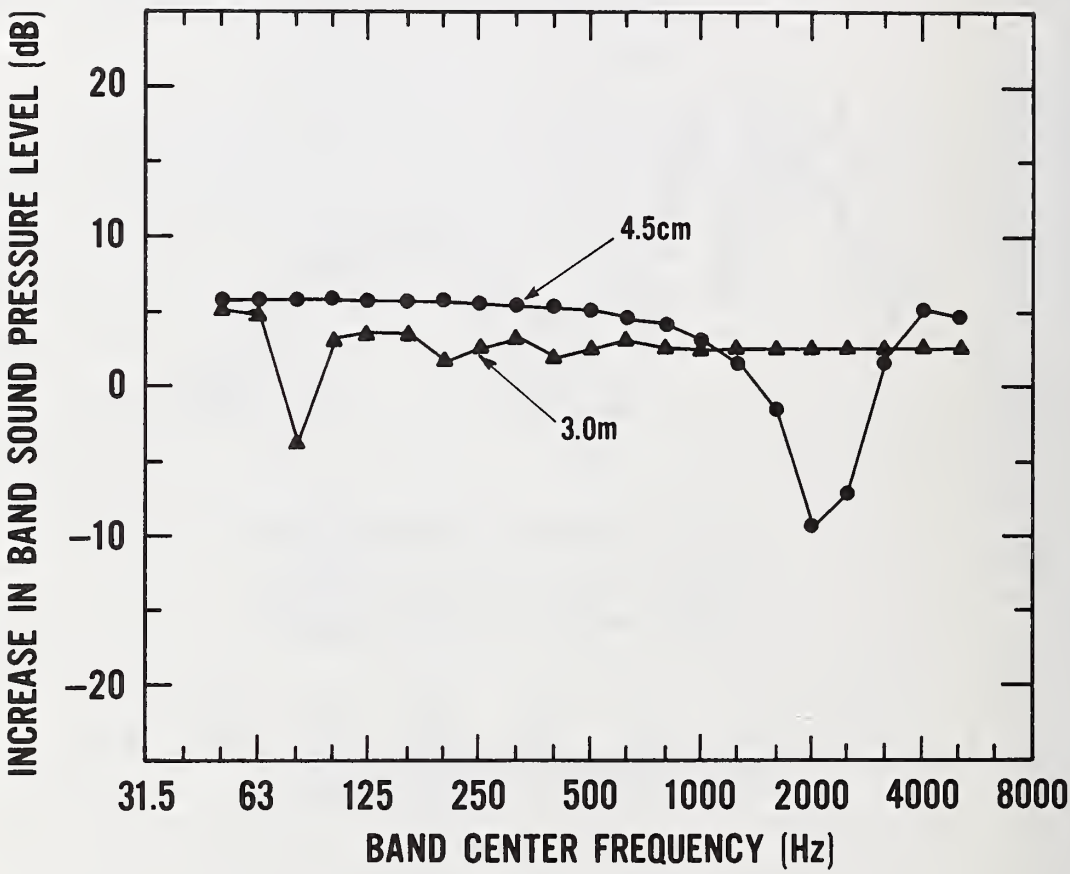

Figure 36. Computed increase in 1/3-octave band sound pressure level due to reflection from an idealized planar surface for microphone positions located 4.5 cm and 3.0 m from the surface.

positions should be about 10 dB. The measured sound pressure levels of Fig. 35 indicate a difference of 5.5 to 6.5 dB for the 80-Hz band. Between 1250 and 3150 Hz, Fig. 36 indicates that the level at the 4.5-cm microphone should be less than that at the 3-m position. This difference is as much as 12 dB in the 2000-Hz band and 9 dB in the 2500-Hz band. This predicted behavior is also indicated in Fig. 35. For the 2000-Hz band the measured level at the 4.5-cm position is 9 to 11 dB lower than that at the 3-m position and the level in the 2500-Hz band is 7 to 9 dB lower.

Figure 35 can also be used to examine the variation in measured level between the two 3-m positions. Below 2000 Hz, the sound pressure levels measured at the two positions are nearly identical, with individual variations of no more than 1.5 dB. At 2000 Hz and above, slightly more variation between the levels at the two positions occurs. For these frequencies, typical variations are 1 to 2 dB. Although these high frequency variations are consistent with the variations attributable to surface irregularities of small depth, variations of this small magnitude could also occur due to other physical phenomena.

Another comparison of sound pressure levels measured simultaneously at three exterior microphone position is shown in Fig. 37 for Test House No. 5, where, in addition to the 3-m positions, a microphone was placed 15 cm from the facade. The increase in level due to reflection from the building facade, as determined from Fig. 32, is plotted in Fig. 38 for the two microphone distances.

As in the previous example of Figs. 35 and 36, much of the variation seen in Fig. 37 in the measured sound pressure levels between the 3-m and 15-cm positions can be attributed to reflections as shown in Fig. 38. Below 250 Hz, the measured sound pressure level at the 15-cm position is greater than that at the 3-m position. Further, for the 500- and 630-Hz bands, the level in Fig. 37 corresponding to the 15-cm position is less than that corresponding to the 3-m position, as is also indicated in Fig. 38. The measured level in the 1000- and 1250-Hz bands is greater for the 15-cm position, as is consistent with the predicted difference of Fig. 38. Above 1250 Hz, with the exception of the 1600-Hz band, the variations indicated in the two figures are also consistent.

A final comparison of measured exterior sound pressure levels is presented in Fig. 39 for Test House No. 6. For this house, two microphones were located 3 m from the building surface and one 1.6 m from the surface. The increased level expected (see Fig. 32) for these two microphone distances is plotted in Fig. 40. As in the previous two examples, the variations between the measured levels at the 3 and 1.6 m positions are consistent with the variations of increased level due to reflections from the building surface. As would be expected from Fig. 40, the measured levels of Fig. 39 show only minimal variation between observations at the two microphone distances. Above 100 Hz, the levels at 1.6 m are consistently within 1 or 2 dB of at least one

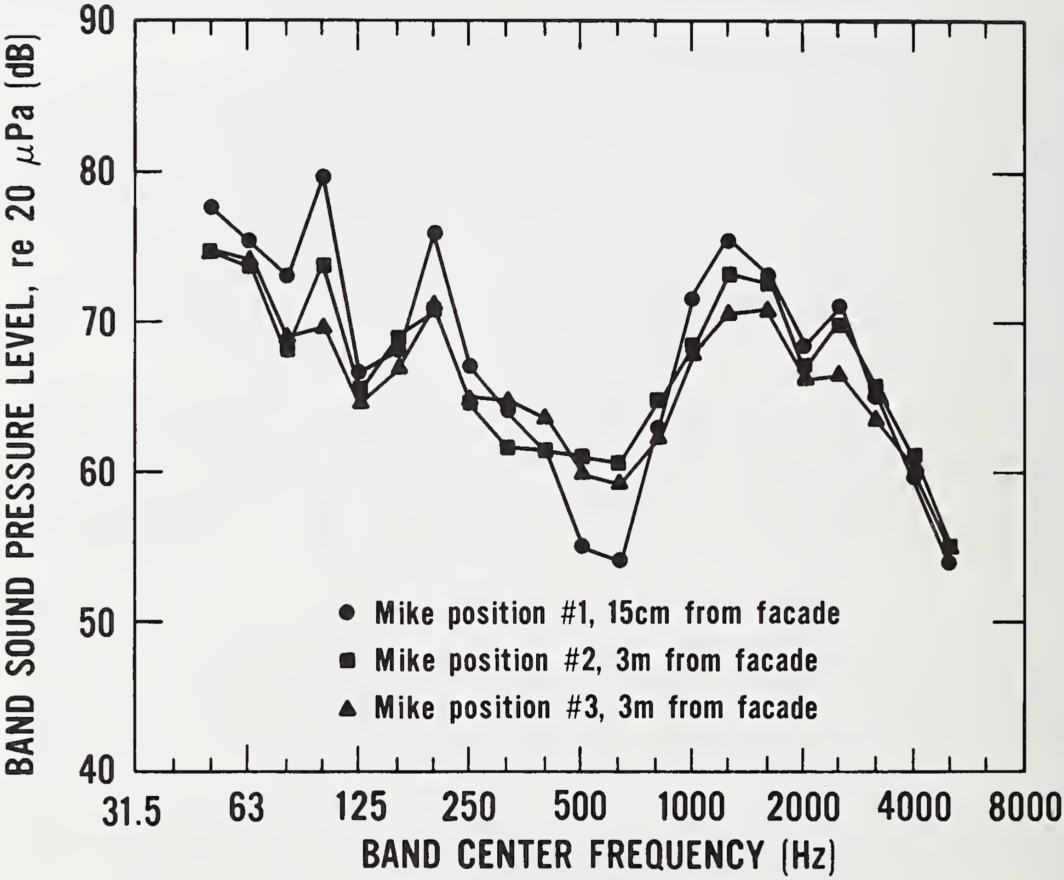

Figure 37. One-third octave band sound pressure levels measured outside Test House No. 5 at three microphone positions at the time of maximum interior A-weighted level.

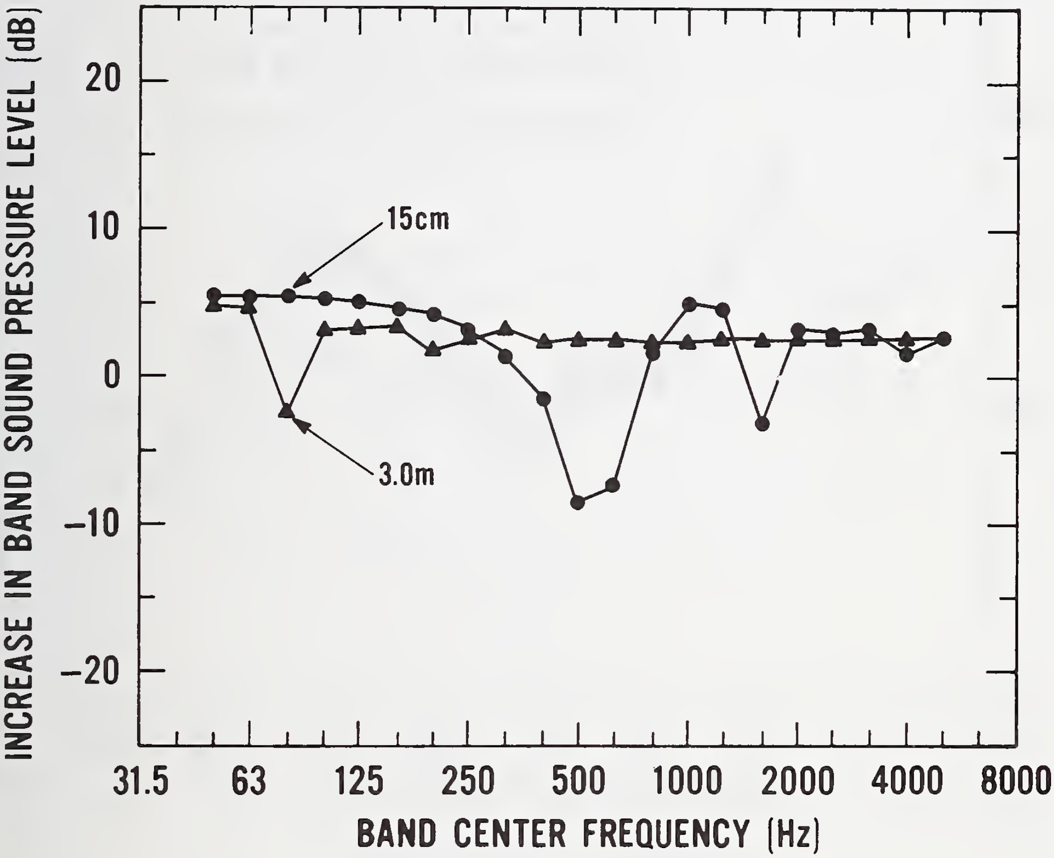

Figure 38. Computed increase in 1/3-octave band sound pressure level due to reflection from an idealized planar surface for microphone positions located 15 cm and 3.0 m from the surface.

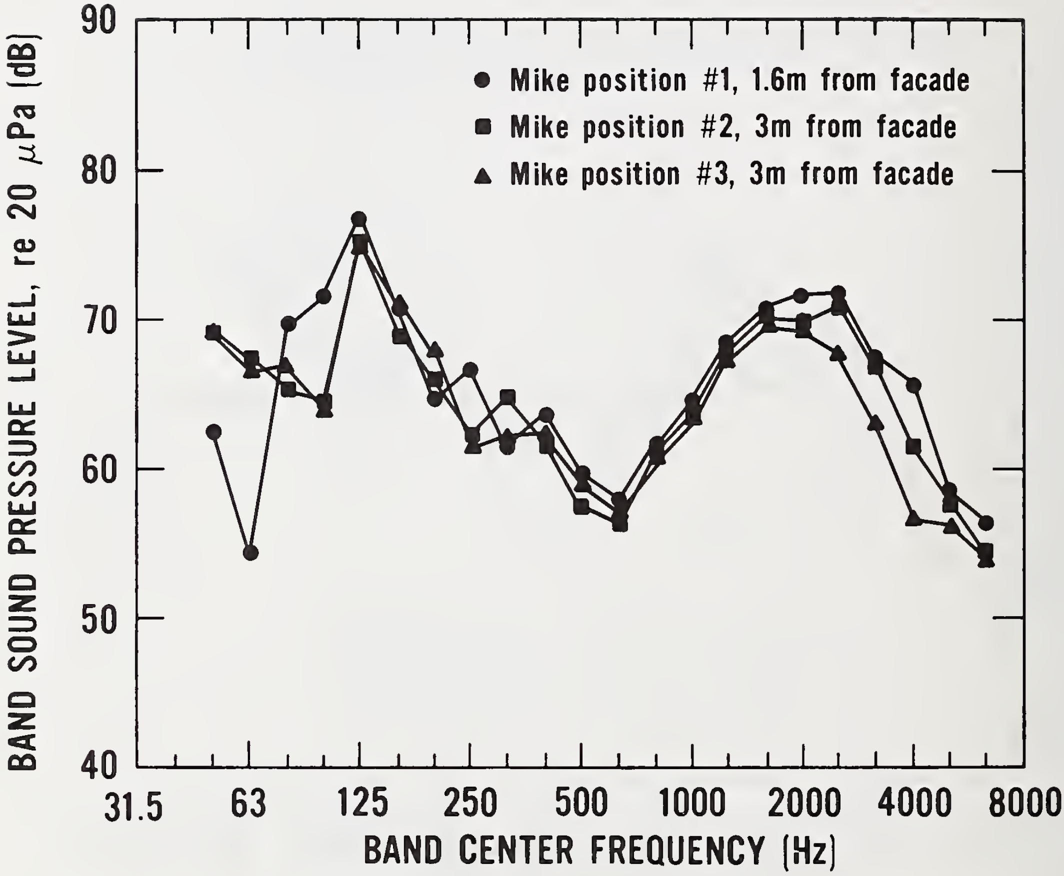

Figure 39. One-third octave band sound pressure levels measured outside Test House No. 8 at three microphone positions at the time of maximum interior A-weighted level.

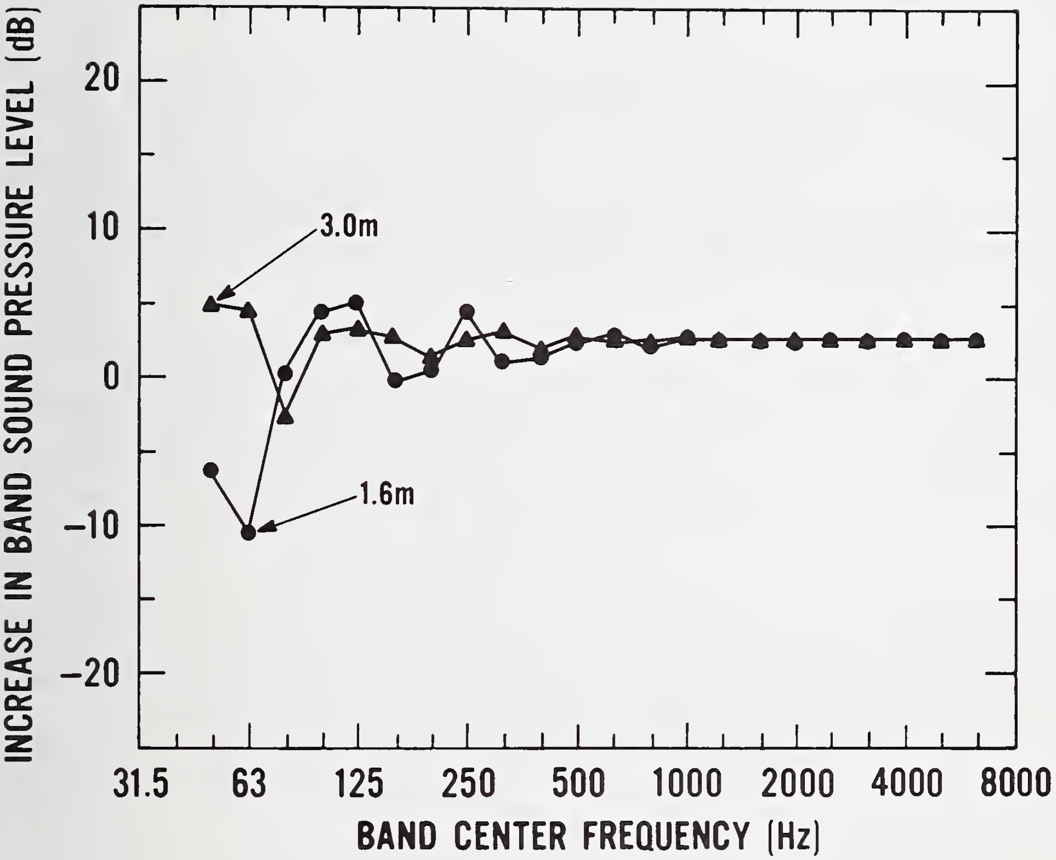

Figure 40. Computed increase in 1/3-octave band sound pressure level due to reflection from an idealized planar surface for microphone positions located 1.6 m and 3.0 m from the surface.

of the levels measured at 3 m, except for the 4000-Hz band. For the 50- and 63-Hz bands, the lower measured levels at the 1.6 m position are also consistent with the difference in increased level due to reflection indicated in Fig. 32. For the 80- and 100-Hz bands, as expected from Fig. 40, the level measured at the 1.6-m position is higher than that at the 3-m positions.

6.1.3 Implications for Sound Isolation Measurements

The results of Secs. 6.1.1 and 6.1.2 can be used to address two sources of uncertainty in the measurement of exterior sound pressure level for the purposes of determining building sound isolation. The first of these uncertainties arises from frequency-dependent interference of the sound directly incident from the source at a given microphone position and that reflected from the vertical building surface. The second of these uncertainties arises from spatial variation of measured sound pressure levels at a fixed distance from the building surface.

In Figs. 35-40, it was shown that the model of reflection from vertical building surfaces as discussed in Sec. 6.1.1 and illustrated in Fig. 32 can be used to estimate the variation in measured sound pressure level for different microphone distances from the building facade. The model can therefore be used to attempt to optimize the distance at which the microphone is placed so as to minimize the variations due to frequency-dependent interference between the direct and reflected sound.

As discussed in Sec. 6.1.1 energy or pressure addition of the direct and reflected sound over the entire frequency range of interest is usually not achievable. It is therefore necessary to select a measurement distance which is practical, minimizes the variation due to interference, and is not too distant from the building facade. For purposes of comparison, the increased level due to reflection is plotted in Fig. 41 for the microphone distances of 2 m (as specified in the ISO and proposed ASTM standards [4,5], 2 cm (as specified as an alternative in the ISO proposal), and 3m (as used in the present study).

The amount of variation in increased level for any one microphone position depends on the frequency range of interest. In the current study, Noise Intrusion Reduction (NIR) was determined from 50 to 4000 Hz. For this frequency range, Fig. 41 indicates that the smallest range of variation occurs for the 3-m position, 8 dB versus 18 dB and 10 dB for the 2-cm and 2-m positions, respectively. For the 2-cm position, the large variation observed occurs above 2000 Hz. Below this frequency, the 2-cm position displays little variation with frequency, less than 2 dB. Variation for the 2-m position is most pronounced below 200 Hz. At 200 Hz and above, the variation in increased level at this position is less than 3 dB. For the 3-m position, the variation above 80 Hz is less than 3 dB.

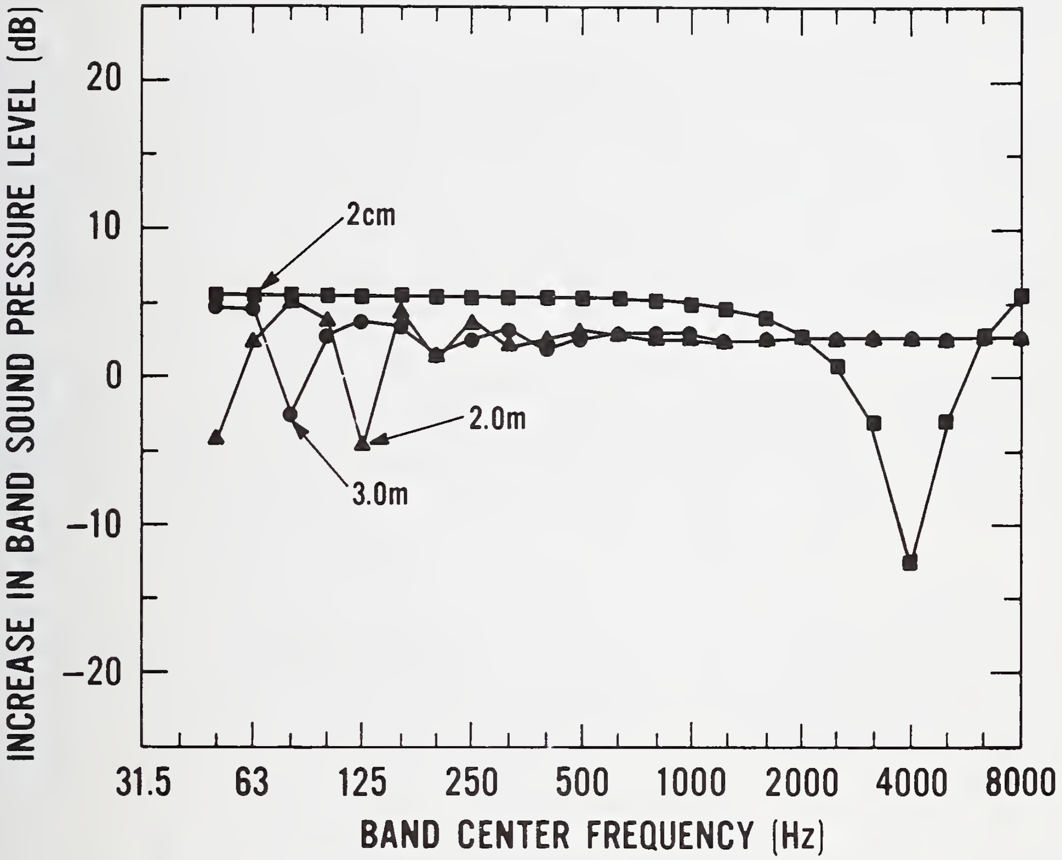

Figure 41. Computed increase in 1/3-octave band sound pressure level due to reflection from an idealized planar surface for microphone positions located 2 cm, 2.0 m, and 3.0 m from the surface.

In the ISO and proposed ASTM standards [4,5], the frequency range of interest is from 100 to 4000 Hz. In this frequency range, significant variations at the 2-m and 2-cm position are present. For the 3-m position, however, the range of variation is small, less than 3 dB, so that this position affords significantly less uncertainty in the measurement of the exterior sound pressure level in the frequency range of typical interest.

The uncertainty due to reflection in the exterior sound pressure level measurement can be minimized by either of two methods. The first is the simultaneous use of more than one microphone distance. From Fig. 36, it is seen that a microphone distance of 4.5 cm or less results in variations of less than 1 dB below 500 Hz, with the increased level corresponding to pressure addition of the direct and reflected sound. At and above 500 Hz, a distance of 2 m or greater also produces variations of less than 1 dB and corresponds to energy addition of the direct and reflected sound. Thus to determine the exterior sound pressure level below 500 Hz, the near microphone position can be used provided that 5.5 dB is subtracted from the measured level to estimate the incident sound pressure level. At and above 500 Hz, the far microphone position can be used provided that 2.5 dB is subtracted to yield an estimate of the incident sound pressure level. Although some uncertainty is introduced into this measurement technique by the assumed increased levels for pressure and energy addition (5.5 and 2.5 dB, respectively), this uncertainty is not expected to be large, at most 3 dB. This should be compared with the 10 to 18 dB variation indicated in Fig. 41 for the 2-m and 2-cm microphone positions. The second method of minimizing uncertainty is to use a distance sufficiently large to yield energy addition throughout the frequency range of interest. In selecting a distance greater than a few meters, however, some uncertainty may be introduced due to differences in sound propagation from the source to the microphone and from the source to the building facade and due to the fact that the building is not a smooth, infinitely-large plane. In the current study, from Figs. 35-40, any variations due to differences in propagation between the 3-m microphone position and those closer to the building were small compared to the variations observed due to differences in interference of the direct and reflected sound at the different microphone distances.

A second source of uncertainty in the measurement of exterior sound pressure levels is the spatial variation of measured level at a fixed distance from the building surface. In Sec. 6.1.2 it was observed that variations of as much as 5 dB occurred between sound pressure levels measured at the two 3-m microphone positions. The cause of this spatial variation cannot be conclusively determined; however, the magnitude of the variation is consistent with that known to occur due to scattered reflection from irregularities in the vertical surface of the building, as discussed in regard to Fig. 34. To reduce the uncertainty in the measured exterior sound pressure level due to spatial variation of the exterior sound field, averaging of the levels measured at several microphone positions can be used. Determination of the number of microphone positions required to reduce significantly the uncertainty in the measured exterior level, however, was beyond the scope of the current study.

6.2 Measurement of Interior Sound Pressure Levels

Uncertainty in the measurement of interior sound pressure level for purposes of determining building sound isolation can be introduced both by spatial variation of the interior sound field and by the dynamic range of the sound pressure levels within the receiving room. From the Noise Intrusion Reduction (NIR) data reported in Appendix B, the spatial variation of the interior sound field is indicated by the variation in NIR seen among individual microphone positions within a given test house. Typically, this variation is more pronounced in the lower frequency bands (200 Hz and below) than in the higher frequency bands. At lower frequencies, spatial variation can occur due to wave phenomena of the sound field within the enclosed space of the receiving room. In the higher frequencies, wave phenomena are of less importance but, particularly in residential rooms where reverberation times are low, spatial variation can occur due to the influence of the direct sound field within the room relative to the reverberant sound field.

The range of interior sound pressure levels, particularly when existing traffic is used as a source of noise, can also result in uncertainty in the interior measurements due to difficult dynamic range requirements for instrumentation and to background noise within the receiving room due to other sources of noise located inside the building.

6.2.1 Spatial Variation at Low Frequency

As an example of the variation in NIR values determined for the three different listener microphone positions within a given receiving room, the values determined for Test House No. 5 (see Appendix C) are presented in Fig. 42. This figure indicates that substantial variation in the measured interior sound pressure levels occurred in the frequency bands below 315 Hz. For the 100-Hz 1/3-octave band, the variation is as great as 16 dB.

At low frequencies, the spatial variation of the sound field in a room can be interpreted in terms of the formal wave-theory solution for a rectilinear closed space [22,36]. Examination of the computed eigenfunctions for the six normal modes that would be expected to exist in the 100-Hz, 1/3-octave band for the dimensions of the room in Test House No. 5 showed qualitative agreement with the results of Fig. 42 for the 100-Hz band.

If the number of normal modes within a 1/3-octave band is small, large spatial variation of the band pressure levels is likely. As the number of modes within a band increases, large spatial variation of the band pressure level becomes less likely. The average number of normal modes, ΔN, within a frequency band, Δf, is given approximately by the expression:

$$\Delta N \simeq \left(\frac{4\pi f^2 V}{c^3} + \frac{\pi f S}{2c^2} + \frac{L}{8c}\right)\Delta f \quad , \qquad (8)$$

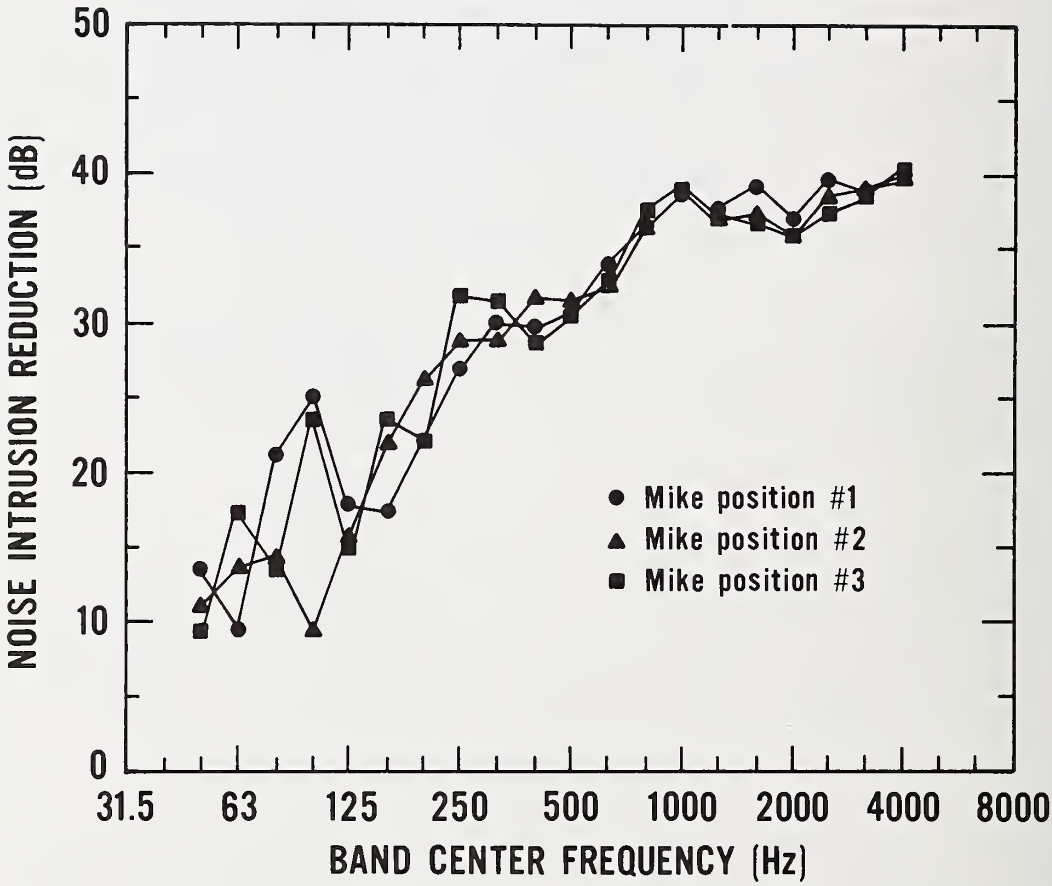

Figure 42. Noise Intrusion Reduction for the three listener positions at Test House No. 5 with windows closed.

where c is the speed of sound, f is the center frequency of the band, V is the room volume, S is the total surface area, and L is the sum of the lengths of all the edges of the room [36]. From this expression, it is seen that the number of modes in a fixed bandwidth increases with both the size of the room and frequency. For 1/3-octave bands, the increase in the number of modes with increasing frequency is further emphasized as the bandwidth also increases in proportion to the band center frequency.

As an example of the increase in the number of modes as a function of frequency for 1/3-octave bands, the average number of modes in a 1/3-octave band, as calculated for Test House No. 5, is plotted in Fig. 43. For the 100-Hz band, the average number of modes within the band is about 6. Above 100 Hz, the average number of modes increases rapidly, reaching about 64 for the 250-Hz band. Because of the rapid increase in the average number of modes with frequency as indicated in Fig. 43, spatial variation in measured sound pressure levels due to wave phenomenon in the room decreases rapidly with frequency.

Substantial uncertainty in measures of building sound isolation can be introduced at low frequencies due to wave phenomena within the receiving room. This uncertainty may be reduced by averaging the mean-square pressure over a number of microphone positions throughout the receiving room. From the data for individual listener positions within each of the nine test houses of the current study, variations in NIR for individual houses were observed to be as much as 7 to 16 dB for 1/3-octave band center frequencies from 50 to 200 Hz. Above these frequencies, spatial variations were observed; however, it is unlikely that at these higher frequencies spatial variations are attributable to normal mode wave phenomena within the receiving room.

6.2.2 Spatial Variation at High Frequency

6.2.2.1 Windows Closed

As indicated in Fig. 42, the variation among NIR values determined at individual interior microphone positions above 250 Hz is typically less than that at lower frequencies. From the data presented in Appendix B, the variation of NIR values among individual listener positions was typically about 3 dB but in some cases was as much as 8 dB.

To obtain some understanding of the sound field within the receiving room for the higher frequencies, sound within the room can be conceptualized as acoustic rays emanating from the source of sound, propagating outward until reflected from a room wall, and then being repeatedly reflected. The sound received, at a point in the room, which comes directly from the source is termed the direct sound field, while sound which is reflected at least once is termed the reverberant sound field [22]. The total mean-square sound pressure at a point a distance r from a source is given by:

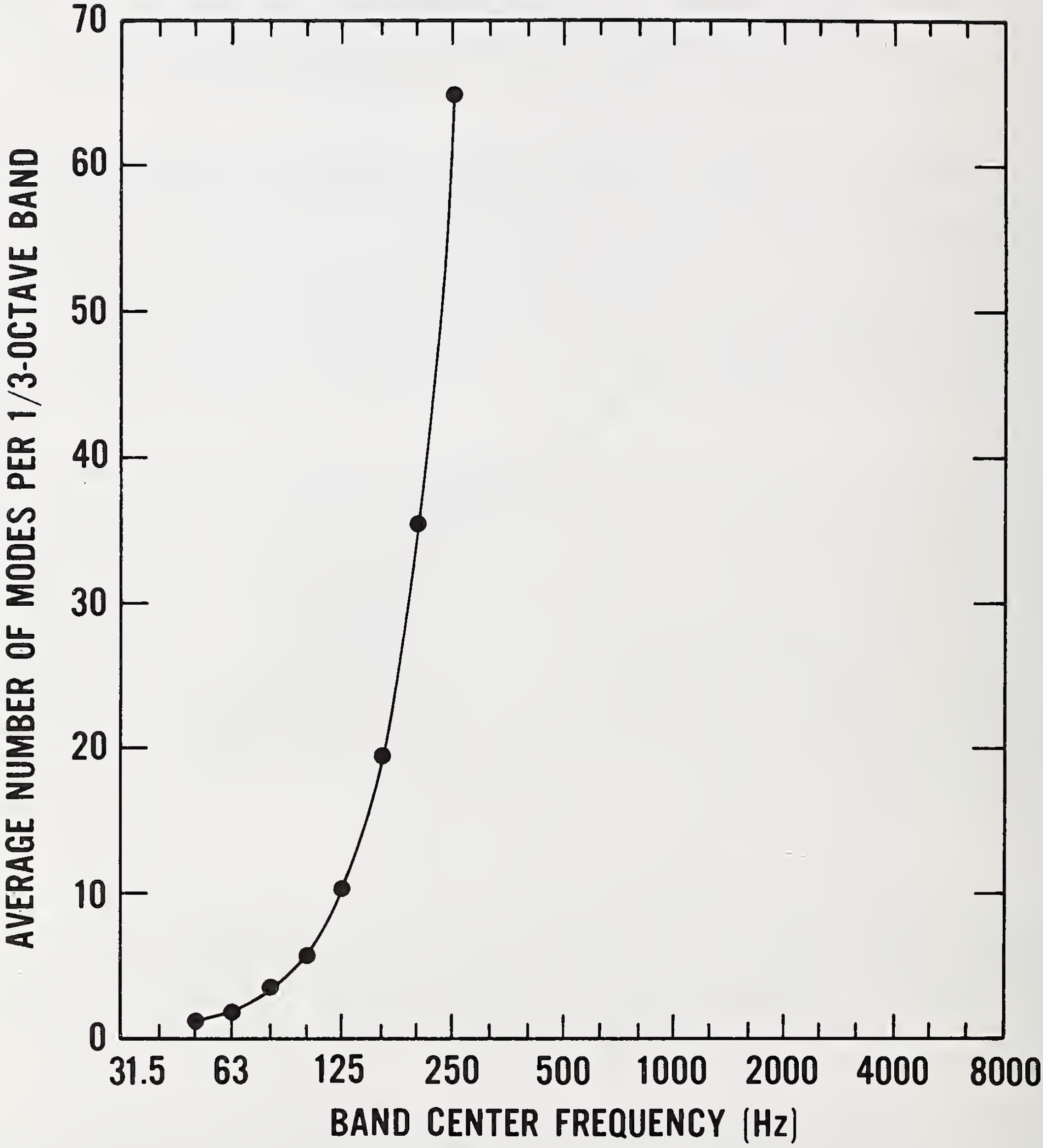

Figure 43. Approximate average number of room modes in a 1/3-octave band for Test House No. 5.

$$p^2 = \rho c W \left[\frac{Q_\theta}{4\pi r^2} + \frac{4}{A} \right] \quad , \tag{9}$$

where ρ is the density of air, c is the speed of sound, W is the acoustic power output of the source, Q_θ is the source directivity factor in a particular direction θ, and A is the total absorption in the room [22]. The first term in Eq. (9) corresponds to the direct field while the second term represents the reverberant field. Based on Eq. (9) with A=27 m^2 (typical for the test houses of this study), relative sound pressure level as a function of distance from the source of noise is plotted in Fig. 44 for values of Q_θ of 1, 4, and 8. For the omni-directional case (i.e., Q_θ=1), the variation of sound pressure level is less than 1 dB at distances greater than 1.5 m from the source. For distances less than 1.5 m, the level increases rapidly as the source is approached, corresponding to increasing influence of the direct sound field of the source.

When the sound field within a receiving room is produced by sources exterior to the building, the sources of noise within the room are building shell elements such as windows, doors, air leaks, etc. When the dimensions of these radiating elements are less than one acoustic wavelength, $Q_\theta \approx 2$, typically [24]. For higher frequencies, as the acoustic wavelength of the source approaches the dimension of the source, the radiation may become even more directive, producing still higher values of Q_θ in certain directions [36]. The effect that higher values of Q_θ have on the fall-off of sound pressure level with distance, in a receiving room typical of those in the current study, is illustrated in Fig. 44 for Q_θ values of 4 and 8. It is seen that as the source becomes more directive, the influence of the direct field of the sound source, relative to the reverberant field in the room, extends farther away from the radiating element. Thus, at 1.5 m from the radiating element, while the sound pressure level due to a point source (Q_θ =1) is only about 1 dB above that of the reverberant field in the room, the levels due to a directive source are 2.5 dB and 4.5 dB above the reverberant values for Q_θ values of 4 and 8, respectively.

Although precise values of Q_θ cannot be readily assigned, Fig. 44 is useful in understanding causes of spatial variation of sound pressure level within the receiving room at higher frequencies. Depending on the directivity of the source, it is seen that the influence of the direct field of a noise source may extend well into a room. If this does occur, then the sound field produced within the room will display a spatial variation due to the distance dependence of the mean-square pressure in the direct field. Furthermore, sound pressure levels measured in the reverberant field will be consistently less then those measured in the direct field of a source. The interior sound field is further complicated when more then one element of the building shell acts as a source of interior noise. In this situation, the level of the reverberant field is determined by the total of the multiple sources while each source has its own direct field and subsequent spatial variation.

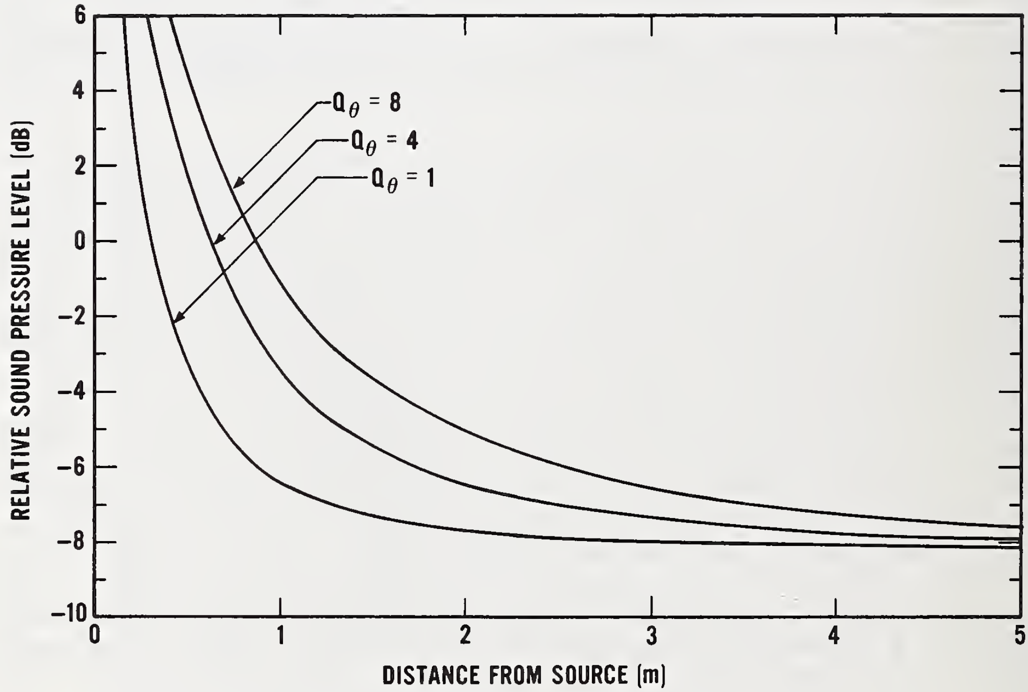

Figure 44. Computed sound pressure level as a function of distance from the source of noise in a hypothetical room (typical of those in the present study) for three values of the directivity factor, Q_θ.

In residential rooms, the interior sound field is still further complicated by furnishings within the test room. Wall and floor coverings such as drapes and rugs and upholstered furniture provide added sound absorption relative to uncovered surfaces, so that sound reflected from such absorptive surfaces is decreased in amplitude relative to that reflected from uncovered surfaces, contributing further to spatial variation. Furnishings also may increase spatial variation by shielding some regions of the room from sound which would have arrived at a microphone position in the absence of these obstacles.

It was not the intent of the current study to quantify these sources of spatial variation or the resultant measurement uncertainty in interior sound pressure levels. However, from the NIR data obtained, spatial variation of sound pressure levels within individual receiving rooms was indicated. For most of the test houses in the current study, the indicated spatial variation was about 3 dB or less above 500 Hz. For one of the test houses, No. 1, the indicated variation was slightly greater, being about 5 dB. As with low-frequency spatial variation discussed in Sec. 6.2.1, uncertainty due to high-frequency spatial variation can be reduced by spatially averaging over a number of microphone positions.

6.2.2.2 Windows Open

The discussion above regarding the high frequency (above 315 to 500 Hz) sound field within the receiving room is also applicable to measurements of building sound isolation with the exterior windows (or doors) open. With the windows open the interior sound field is strongly dominated by sound transmitted through the open windows. An example of the indicated spatial variation with windows open is presented in Fig. 45 for Test House No. 2, where NIR values determined at the three interior listener microphone positions are plotted. The approximate location of these three microphone positions, relative to the open windows, is presented in Fig. 46.

In Fig. 45, substantial spatial variation is indicated both at low and high frequency. The variation below 315 Hz is similar to that noted for test houses with windows closed, as discussed in Sec. 6.2.1. Above 800 Hz, the indicated spatial variation is considerably larger than that typically observed with the windows closed. Above 1600 Hz, the indicated variation is about 7 to 9 dB compared to about 2 to 4 dB with the windows closed for this house (see Appendix C).

The increased high frequency spatial variation in Fig. 45 with windows open can be readily interpreted using the high frequency assumption of ray acoustics as described in Sec. 6.2.2.1. For the data of Fig. 45, the acoustic rays emanating from the test vehicle nominally impinge at normal incidence on the front of the building. Those rays which are not reflected by the building propagate directly through the two open windows into the room until reflected by a wall. At sufficiently high frequencies, the rays

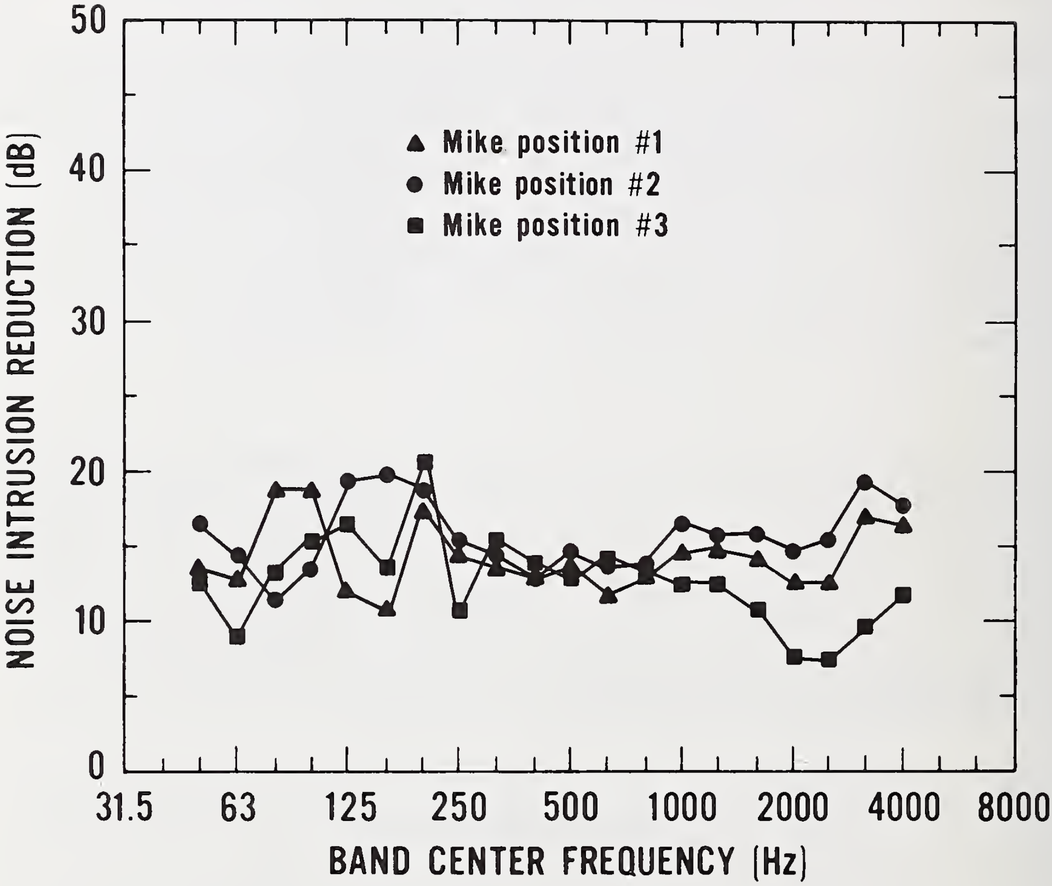

Figure 45. Noise Intrusion Reduction for the three listener positions at Test House No. 2 with the windows open.

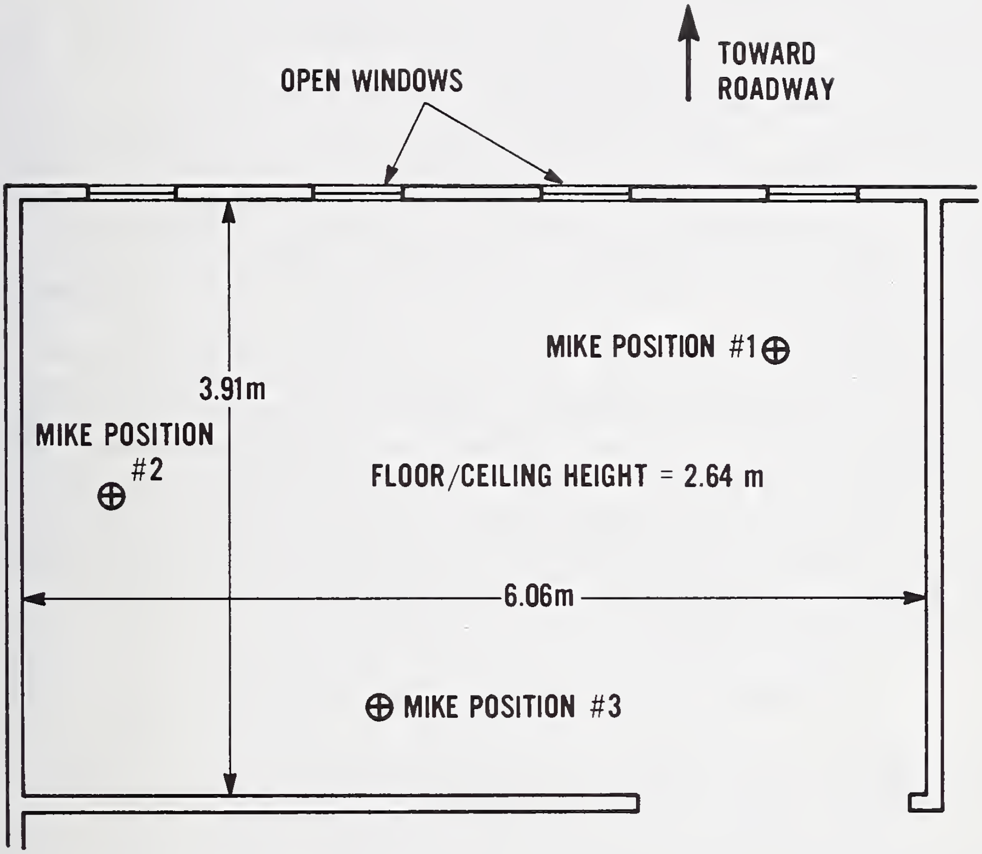

Figure 46. Floor plan and listener position microphone locations for Test House No. 2.

would be confined to a beam of cross-section approximately equal to that of the window opening and extending across the room. Thus, the microphone at position No. 3 would be directly exposed to the sound transmitted in this beam and the measured level would have a correspondingly high value. For microphone positions out of the beam formed by the open window, the measured sound pressure level would be a combination of sound diffracted around the edge of the open window and sound which is reflected from the interior surfaces and furnishings of the rooms. As both the diffracted and reflected sound are of less amplitude than the direct sound, microphone positions not in the direct beam from the open windows are expected to correspond to smaller values of sound pressure level. Such behavior is indicated in the data of Fig. 44. The values of NIR determined at position No. 3 are significantly lower than those determined at positions No. 1 and No. 2, which are not in the direct beam of the open window. Above 1600 Hz, the values at position No. 3 are 6 to 9 dB lower than those for the other two positions. For the 1/3-octave bands centered at 1000, 1250 and 1600 Hz, the values at position No. 3 are also lower, but only by 2 to 5 dB. At these frequencies, since the acoustic wavelengths are on the order of the window opening dimension, diffraction is expected to be more pronounced than at higher frequencies.

From the data and discussion above, it is seen that the uncertainty in the measurement of interior sound pressure level for high frequencies (above 800 Hz) is increased when the exterior windows are open relative to that when the windows are closed. When the exterior windows are closed, variation in sound pressure levels among listener position microphones was found to be typically 3-4 dB. With the windows open, for one of the test houses, the spatial variation was found to be as much as 9 dB at frequencies above 1600 Hz. For measures of building sound isolation with windows or doors open, the increased spatial variation, and hence measurement uncertainty, in the high frequency should be considered.

6.2.3 Magnitude of Interior Sound Pressure Levels

A final source of certainty in the measurement of interior sound pressure levels for the purposes of determining measures of building sound isolation is the magnitude of the interior sound pressure levels. In measuring interior levels, background noise of similar magnitude to the noise produced by the exterior source may be present due to existing sources of sound within the building. Also, due to the frequency dependency of the sound isolation performance of building shells, measurement of the interior sound pressure levels can require a large instrumentation dynamic range. The uncertainty due to these two causes is particularly accentuated when existing traffic outside of the building is used as the source of exterior noise.

6.2.3.1 Dynamic Range Requirement

To examine the dynamic range requirements for the interior sound pressure level measurement, a 1/3-octave band traffic noise equivalent sound level spectrum was selected. This spectrum was taken from the traffic noise data base obtained as part of the overall program of which the current report was part [2]. The spectrum was chosen to represent a mix of vehicle types traveling at low speed (posted limit of 64 km/hr.) as might be encountered on an arterial street. The data are presented in Fig. 47 as obtained 15 m from the roadway. In addition, the 1/3-octave

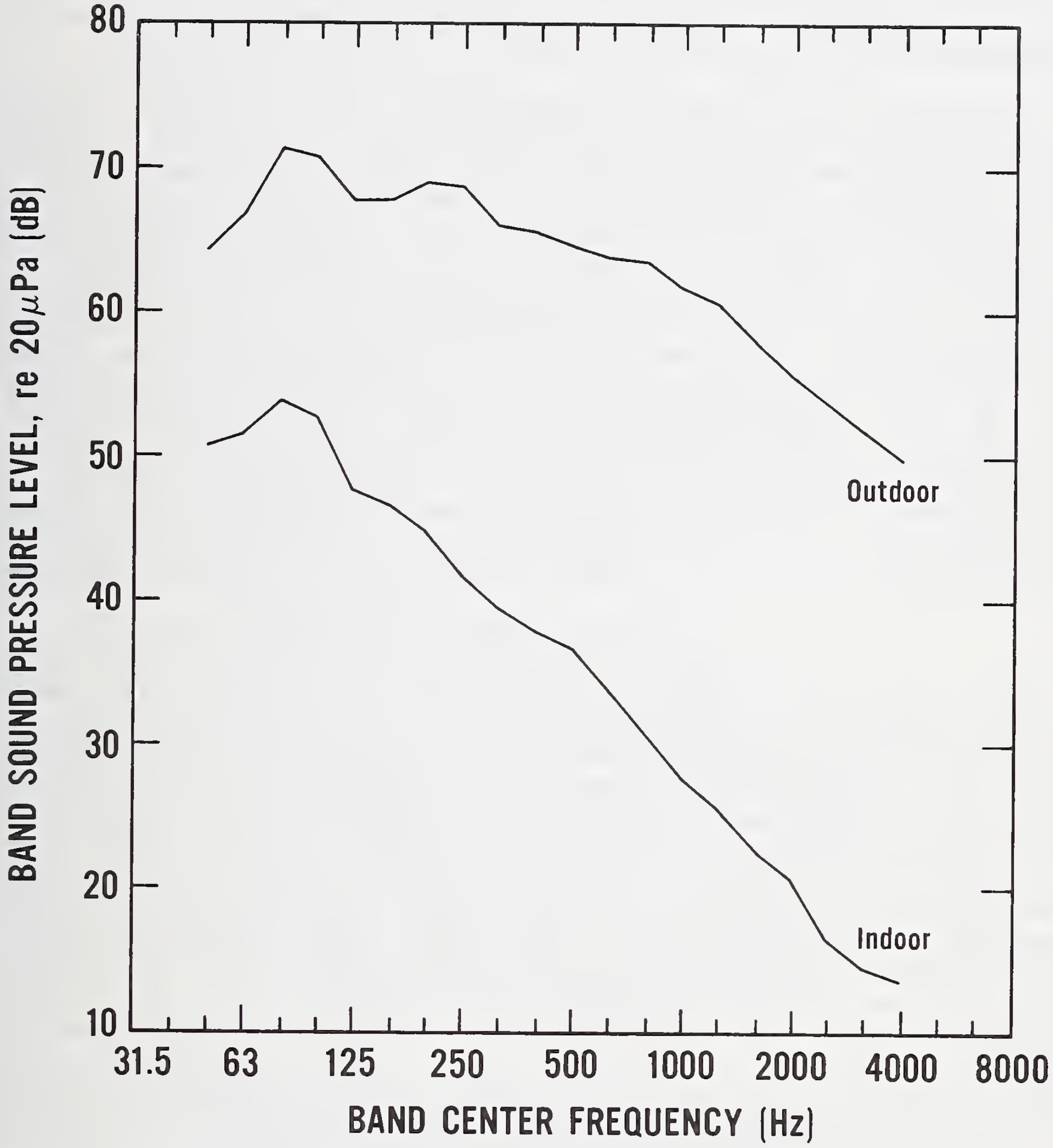

Figure 47. Traffic noise equivalent sound level spectra as measured outdoors and as estimated indoors from average Noise Intrusion Reduction values for the nine test houses. The outdoor spectrum corresponds to a recording taken 15 m from the centerline of the near lane of Gude Drive with an average traffic speed of 64 km/hr and an average traffic flow of 510 vehicles per hour (84.4% automobiles, 2.8% medium trucks, and 12.8% heavy trucks) [2].

band spectrum obtained by subtracting the average NIR values reported in Fig. 14 from the traffic levels is also presented in Fig. 47. The resultant, illustrative indoor spectrum can be used to consider the influence of background noise on the interior sound pressure level measurement.

From Fig. 47 it is seen that although the outdoor spectrum covers a range in level of about 21 dB over the frequency range from 50 to 4000 Hz, the indoor spectrum covers a range of about 40 dB. This requires that the instrumentation used to measure the interior sound pressure levels have a dynamic range of greater than 40 dB. This requirement is further extended as temporal variations in the level will occur which require additional dynamic range. For the traffic noise reported in Fig. 47, the level exceeded 1 percent of the time in individual 1/3-octave bands was typically 10 dB greater than the equivalent level in the corresponding band. Thus the total dynamic range required to measure the interior sound pressure levels of Fig. 47 would be greater than 50 dB. With such dynamic range requirements, particular attention must be given to the characteristics of the instrumentation employed in measures of building sound isolation when existing traffic is used as the source of exterior noise. If the dynamic range requirements are not adequately addressed, uncertainty in the sound isolation measure can occur due to the limitations of the instrumentation.

6.2.3.2 Background Noise within the Receiving Room

The range of background 1/3-octave band sound pressure levels measured at each of the nine test houses is presented in Fig. 48. Typically, this range has a magnitude on the order of 10 dB and indicates some frequency dependence. Also presented in Fig. 48 is the indoor sound pressure levels determined from the traffic noise equivalent sound levels of Fig. 46 and the average NIR values of the current study. Although this resultant indoor spectrum is not necessarily typical of that which occurs in any given house, it does illustrate the difficulty which could occur due to the presence of background noise in the receiving room when existing traffic noise is used as the source of exterior noise. It is seen that, for this indoor spectrum, the values are greater than the upper limit of the range of background noise for frequencies below 2500 Hz. However, between 800 and 2500 Hz, the level due to traffic noise is only a few decibels greater than the upper limit. If the traffic noise of Fig. 47 were actually measured in a house with background noise levels similar to those of the upper limit of the range of background noise from the nine test houses, the level measured inside would be increased by the background noise above 800 Hz.

To reduce the uncertainty in building sound isolation resulting from the presence of background noise within the receiving room, the background noise due to sources within the building should be determined. However, if the building is exposed to continual traffic or other environmental noise, this background level cannot be readily determined due to the continuing intrusion of the exterior noise. In this circumstance, the use of a loudspeaker or other controllable exterior source of noise may be required to eliminate the uncertainty created by background noise within the building.

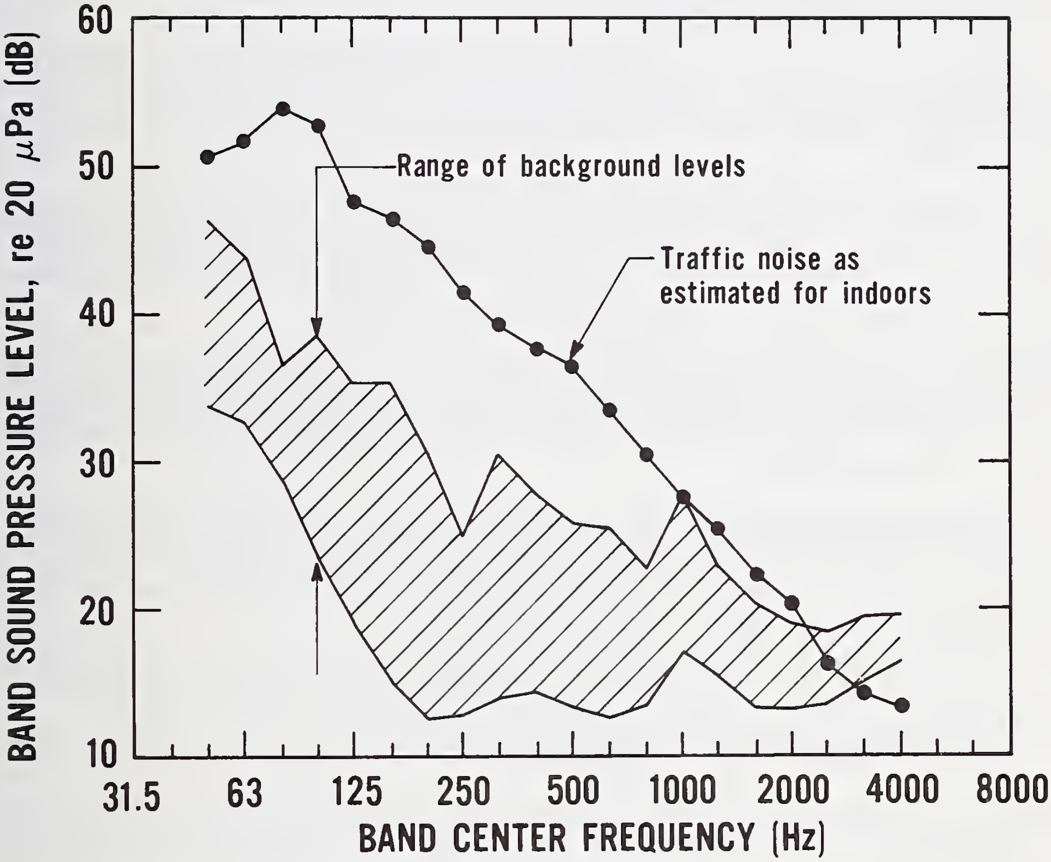

Figure 48 . Range of 1/3-octave band sound pressure levels of background noise for the nine test houses compared with estimated indoor spectrum for exterior traffic noise (from Fig. 47).

7. References

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Appendix A. Floor Plans For The Nine Test Houses

Contained in this Appendix are the room floor plans for the nine test houses for which Noise Intrusion Reduction values were obtained as described in Section 3. For Test House No. 8, an interior elevation is also presented as the ceiling and floor are not parallel. The window dimensions are indicated in the figures using the following symbols:

a = distance from the floor to the base of the window opening

h = height of the window opening

b = distance from the ceiling to the top of the window opening.

The symbol H in the figures is used to denote the floor to ceiling dimension. The construction details of each of the nine test houses are summarized in Table 1 of Section 3.2. The top of each figure corresponds to the side of the house which faces the road.

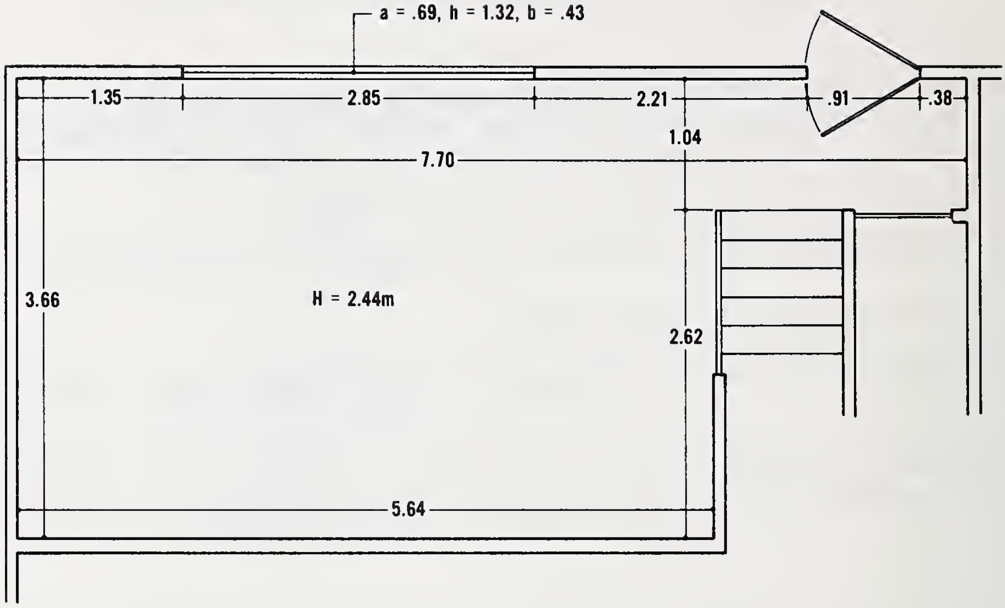

Figure A1. Floor plan for Test House No. 1.

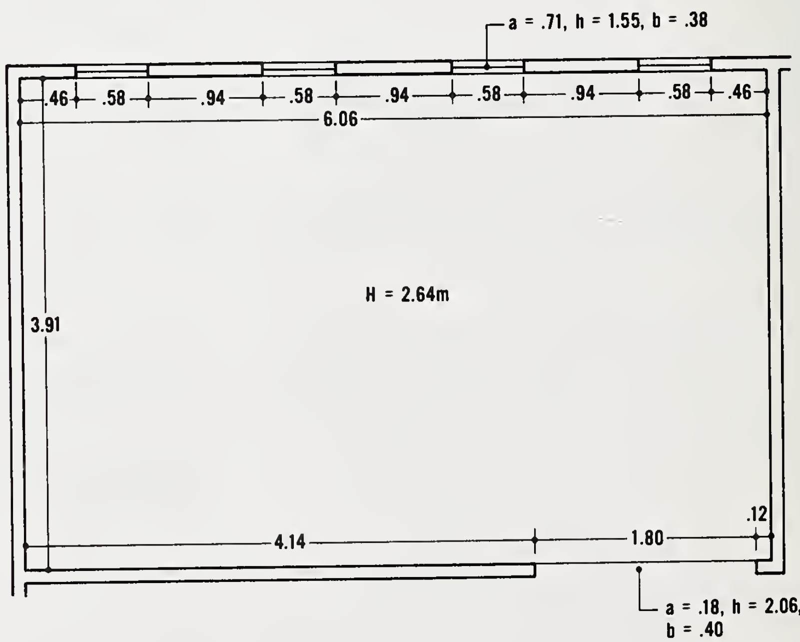

Figure A2. Floor plan for Test House No. 2.

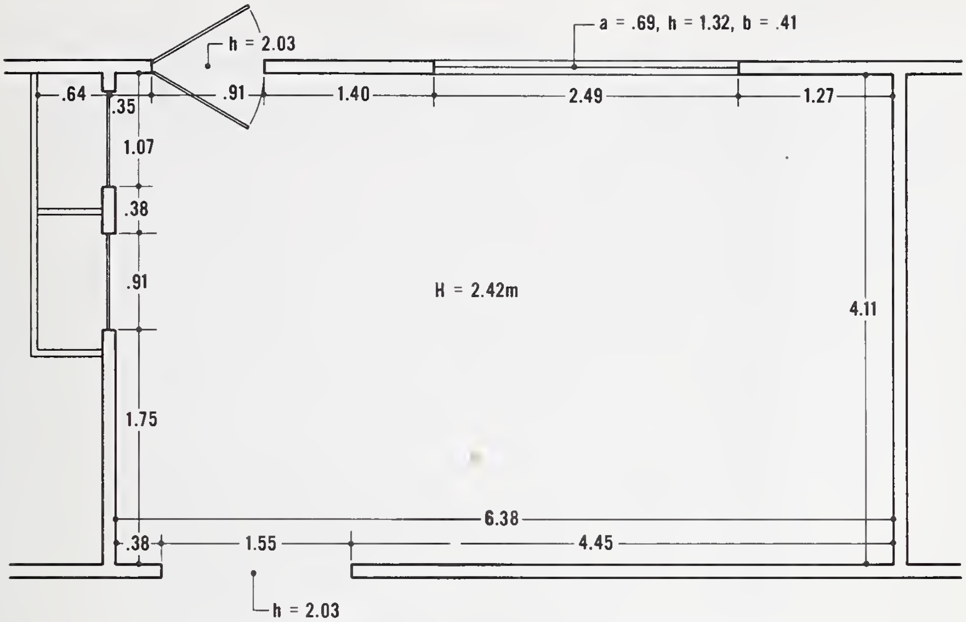

Figure A3. Floor plan for Test House No. 3.

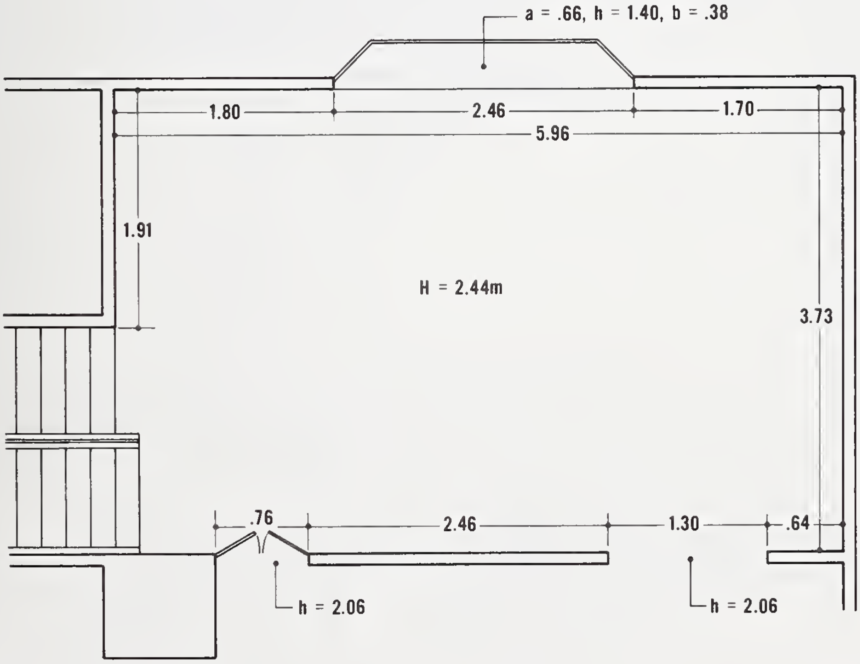

Figure A4. Floor plan for Test House No. 4.

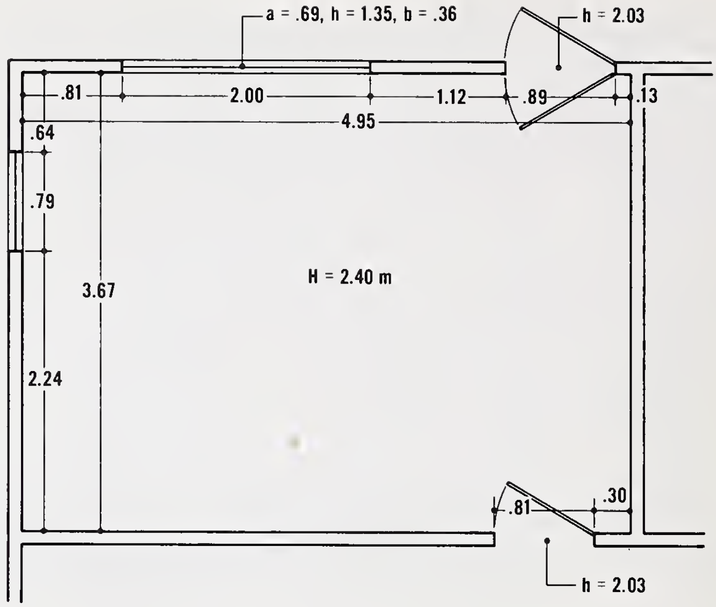

Figure A5. Floor plan for Test House No. 5.

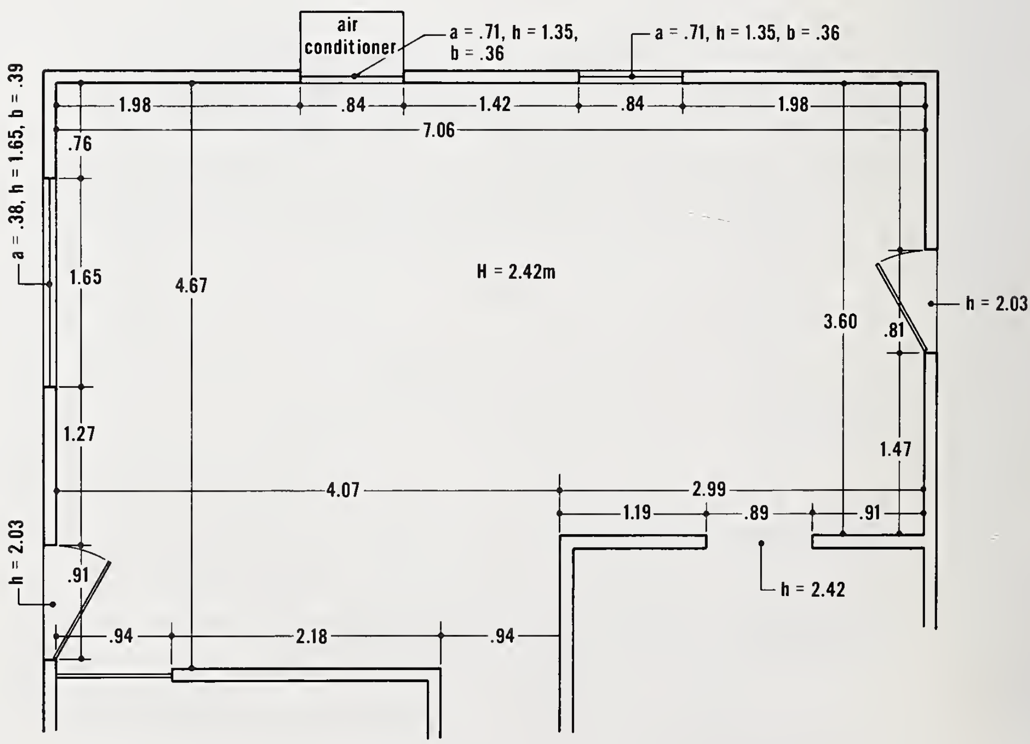

Figure A5. Floor plan for Test House No. 6.

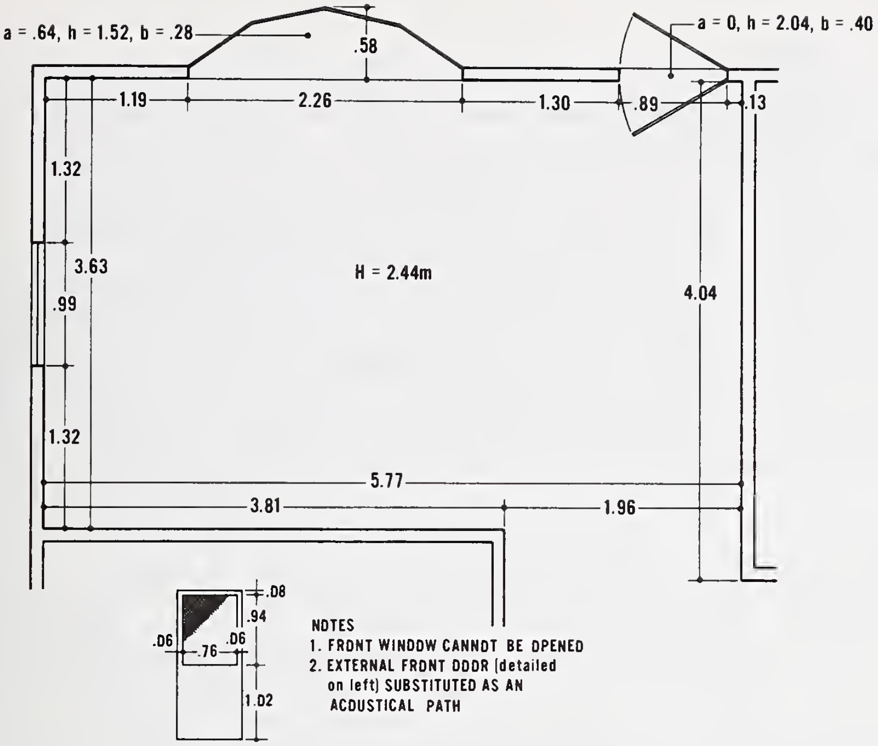

Figure A7. Floor plan for Test House No. 7.

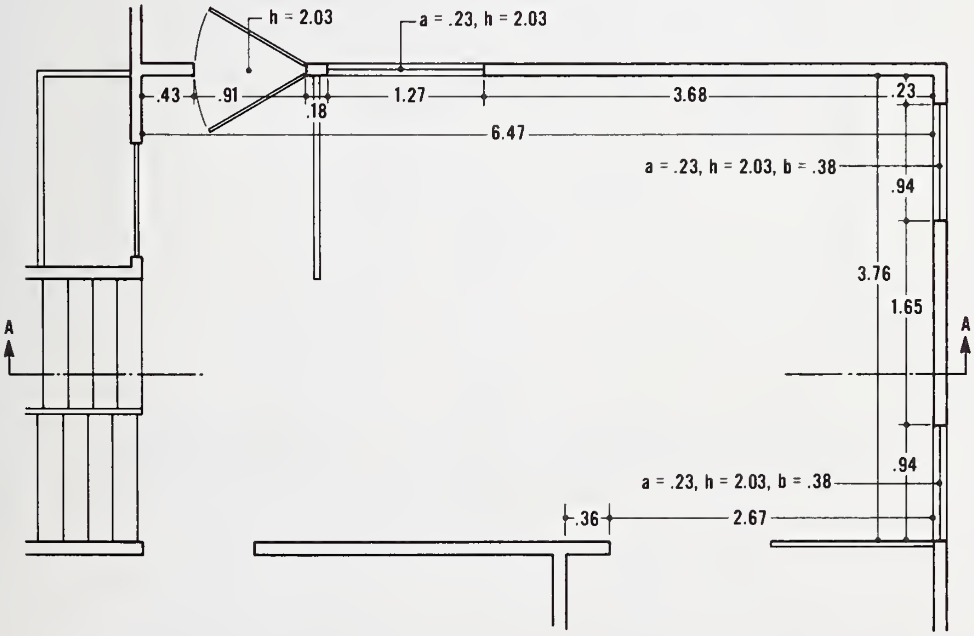

Figure A8. Floor plan for Test House No. 8.

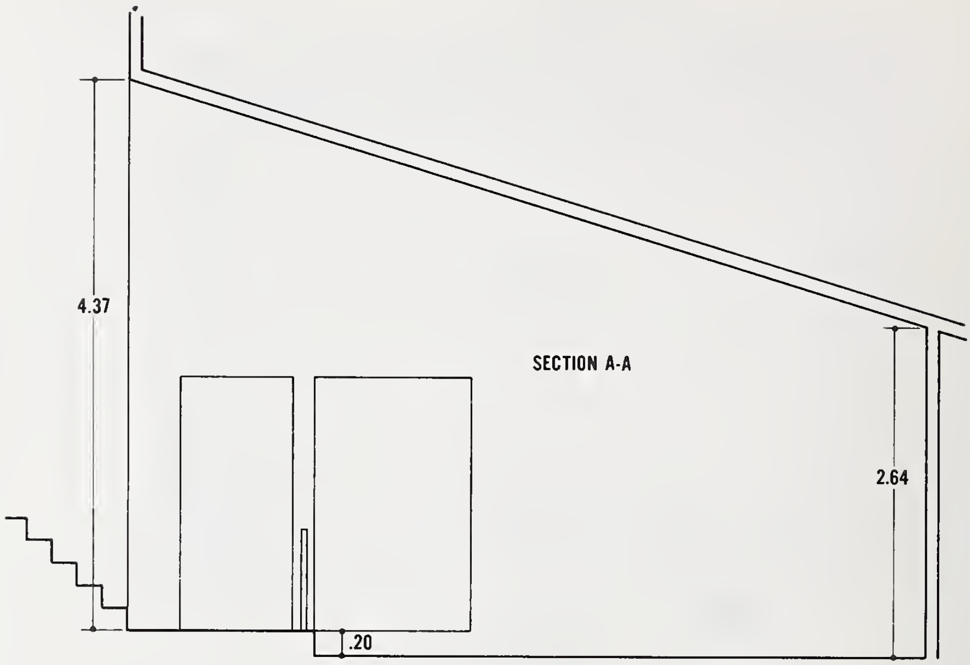

Figure A9. Interior elevation for Test House No. 8.

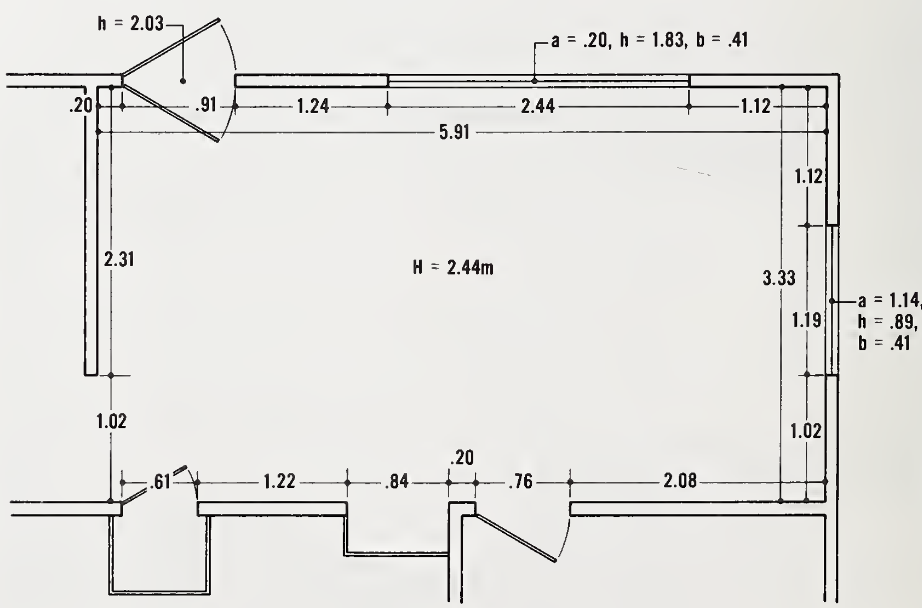

Figure A10. Floor plan for Test House No. 9.

Appendix B. Values of Noise Intrusion Reduction Determined With Simultaneously Occurring Outdoor and Indoor Sound Pressure Levels

The NIR values presented in this Appendix were obtained from the sound pressure levels measured simultaneously at the exterior and interior microphone positions and correspond to Data Set No. 1 of Section 3.3. The 1/3-octave band values of NIR from 50 to 4000 Hz obtained with this data reduction technique are presented in Tables B1 through B18. In each table values of the average outside sound pressure level at the two 3-m microphone positions, NIR values at the interior reference position, and NIR values at each of the three interior listener positions are presented. The average NIR for the three listener positions is also presented as calculated from Eq. (4) of Section 4.1.1.

The values reported in Tables B1-B8 and B13-B18 were determined using the sound pressure levels which occurred at the instant of maximum interior A-weighted sound level for the reference position microphone. The values presented in Tables B9-B12 for Test House No. 8 were determined using simultaneously-occurring sound pressure levels during a passby of the test vehicle at four instances other than when the maximum interior level occurred. Tables B13-B17 present the values determined for five different passbys of Test House No. 5. Table B18 presents values obtained with the front door of Test House No. 9 open.

Also included in this Appendix are plots of the NIR values averaged over the three listener positions for each of the nine test houses. These are presented in Figures B1-B9.

Table B1. Noise Intrusion Reduction Data Set No. 1, Test House No. 1

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	59.8	8.8	7.3	9.5	6.5	7.6
63	61.2	17.6	15.4	13.4	12.5	13.6
80	58.4	18.2	23.4	17.6	22.6	20.4
100	61.9	22.2	24.4	23.1	21.4	22.8
125	62.3	20.3	23.0	21.7	23.0	22.5
160	61.6	23.6	19.3	18.6	16.6	18.0
200	61.0	27.0	22.5	23.7	24.3	23.4
250	66.0	27.0	31.0	30.4	28.0	29.6
315	66.9	25.7	31.2	29.3	27.6	29.1
400	62.1	30.9	27.8	27.3	26.7	27.2
500	63.3	28.3	29.3	27.5	24.8	26.8
630	62.7	26.0	28.4	26.9	25.2	26.6
800	63.3	29.9	32.8	27.0	29.2	29.1
1000	63.3	29.8	32.8	29.0	29.0	29.9
1250	64.4	28.7	33.7	29.6	32.2	31.5
1600	64.4	33.4	35.1	32.1	35.5	34.0
2000	60.8	32.8	34.5	31.5	31.8	32.4
2500	56.6	30.2	-	29.0	29.3	29.1
3150	55.0	29.6	-	29.4	28.5	28.9
4000	52.5	-	-	27.9	27.2	27.5

Table B2. Noise Intrusion Reduction Data Set No.1, Test House No.2

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, DB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	69.8	14.8	19.2	21.8	20.0	20.2
63	61.6	12.3	23.0	14.6	21.1	18.0
80	73.1	23.6	24.8	14.4	19.6	17.7
100	74.8	31.3	38.4	28.4	26.6	29.0
125	76.4	26.2	24.8	28.2	28.2	26.8
160	69.8	23.0	22.2	23.8	27.4	24.0
200	78.4	20.8	27.4	21.4	26.3	24.2
250	69.5	24.7	27.9	26.3	24.3	25.9
315	59.8	22.8	25.0	26.4	21.5	23.8
400	56.6	19.6	20.6	22.9	26.4	22.7
500	61.7	27.2	29.1	28.3	23.9	26.5
630	59.1	24.3	29.5	29.9	26.9	28.6
800	65.8	37.6	32.2	31.4	31.0	31.5
1000	69.0	34.5	34.2	36.0	34.2	34.7
1250	70.8	33.3	33.0	37.6	36.8	35.3
1600	68.9	32.1	32.1	37.7	35.4	34.5
2000	70.0	34.2	30.7	37.8	36.0	33.7
2500	67.2	31.4	28.9	35.0	35.7	32.0
3150	61.6	28.8	28.3	32.6	30.8	30.2
4000	59.5	30.7	30.5	33.8	32.3	32.0

Table B3. Noise Intrusion Reduction Data Set No.1, Test House No.3

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	52.5	16.0	19.5	-	-	-
63	63.4	27.6	28.6	25.3	26.5	26.6
80	53.7	24.0	16.9	22.4	16.5	17.9
100	70.6	27.1	30.4	29.6	29.4	29.8
125	62.5	26.5	25.7	29.2	25.5	26.5
160	76.4	19.1	20.9	22.6	21.4	21.6
200	64.3	9.6	18.5	21.7	14.9	17.5
250	57.0	15.3	26.0	27.0	22.6	24.8
315	52.9	25.9	-	-	-	-
400	46.3	-	-	-	-	-
500	46.2	-	-	-	-	-
630	47.2	-	-	-	-	-
800	49.9	-	-	-	-	-
1000	56.4	30.7	31.4	32.6	-	32.0
1250	61.2	35.7	35.4	35.4	35.0	35.3
1600	64.0	37.3	38.0	38.4	38.3	38.2
2000	64.0	33.5	34.0	35.2	35.3	34.8
2500	64.8	34.5	35.0	36.2	37.4	36.1
3150	62.3	35.8	36.5	36.3	35.9	36.2
4000	57.2	-	-	-	-	-

Table B4. Noise Intrusion Reduction, Data Set No.1, Test House No.4

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	66.9	14.9	16.9	13.4	17.4	15.5
63	63.0	14.2	15.5	20.2	23.0	18.5
80	72.2	16.9	14.2	24.7	25.0	18.3
100	66.9	18.3	22.4	20.9	20.1	21.0
125	78.8	19.5	26.3	19.2	17.3	19.6
160	68.1	22.3	26.3	20.9	19.1	21.2
200	74.8	16.8	23.6	22.6	21.0	22.3
250	69.6	16.0	29.8	26.8	22.6	25.4
315	65.6	18.0	26.5	31.8	25.4	27.1
400	66.4	23.6	32.2	33.4	31.6	32.3
500	63.7	25.9	32.9	27.5	31.2	29.9
630	60.9	26.1	32.1	31.7	33.9	32.5
800	66.6	29.6	37.1	33.4	35.1	34.9
1000	70.9	32.3	40.1	35.7	37.4	37.4
1250	75.0	33.7	40.2	38.0	39.5	39.1
1600	73.2	34.4	42.7	40.2	41.7	41.4
2000	68.6	32.3	36.8	36.8	33.8	35.6
2500	69.8	32.8	38.8	38.8	36.3	37.8
3150	69.4	34.8	40.6	38.4	37.9	38.8
4000	65.3	33.0	38.8	37.3	36.3	37.3

Table B5. Noise Intrusion Reduction, Data Set No.1, Test House No.5

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	74.3	12.6	13.3	12.1	10.1	11.6
63	73.9	22.7	16.9	19.2	22.9	19.0
80	68.4	23.7	21.2	18.4	15.2	17.6
100	72.2	17.2	27.2	14.0	21.7	17.9
125	64.9	21.2	23.7	20.9	23.9	22.6
160	68.0	17.3	24.8	21.5	21.3	22.3
200	70.9	18.7	25.7	23.9	19.4	22.2
250	64.8	28.6	30.3	28.3	28.6	29.0
315	63.5	28.8	33.3	31.0	30.5	31.4
400	62.6	25.6	33.6	30.6	29.9	31.1
500	60.5	30.8	35.3	32.5	32.3	33.2
630	59.9	33.2	35.4	35.9	34.7	35.3
800	63.7	35.0	36.2	35.7	37.0	36.8
1000	68.1	35.9	36.1	37.4	37.1	36.8
1250	71.9	33.9	36.2	36.2	35.4	35.9
1600	71.7	36.5	37.7	36.0	35.5	36.3
2000	66.8	31.1	32.3	32.1	31.3	31.9
2500	68.5	35.0	35.5	34.3	32.5	33.9
3150	64.7	35.0	33.7	33.7	30.5	33.6
4000	60.8	35.8	34.6	34.8	34.1	34.5

Table B6. Noise Intrusion Reduction, Data Set No.1, Test House No.6

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	69.0	11.2	14.3	19.2	11.8	14.2
63	66.9	18.4	21.9	22.9	17.0	19.8
80	66.1	8.6	10.1	9.7	12.2	10.5
100	63.6	6.1	8.6	8.4	9.7	8.9
125	74.9	28.9	23.6	25.1	27.4	25.1
160	69.9	23.9	16.9	21.4	21.0	19.3
200	67.1	20.9	21.8	21.3	24.9	22.4
250	61.9	19.4	20.9	20.7	19.0	20.1
315	63.6	20.8	30.1	30.1	23.4	26.6
400	61.8	23.8	29.3	29.6	29.1	29.3
500	58.3	28.1	29.6	30.1	29.1	29.6
630	56.8	27.8	27.8	27.8	30.3	28.5
800	61.0	29.8	30.7	31.5	32.8	31.6
1000	63.4	29.6	30.4	30.9	32.7	31.2
1250	67.7	29.5	33.7	29.5	33.2	31.7
1600	69.8	34.0	35.3	33.3	34.9	34.4
2000	69.5	32.3	32.5	28.3	34.0	30.9
2500	69.5	35.0	37.0	35.0	38.0	36.5
3150	65.4	33.4	34.9	35.6	33.9	34.7
4000	59.7	32.7	30.7	30.9	33.2	31.5

Table B7. Noise Intrusion Reduction, Data Set No.1, Test House No.7

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	69.1	13.6	12.3	15.3	15.3	14.1
63	71.2	13.2	12.7	16.0	15.0	14.3
80	63.1	14.1	11.9	17.9	18.1	14.9
100	68.9	14.4	16.4	13.4	22.4	16.1
125	67.0	30.5	30.2	20.2	19.5	21.4
160	67.4	28.2	31.9	34.9	23.9	27.7
200	78.1	32.3	36.3	39.6	24.9	29.2
250	66.0	28.0	28.5	22.0	29.8	25.3
315	60.8	25.8	30.3	26.8	28.6	28.3
400	62.2	25.7	35.4	30.4	27.7	30.1
500	58.0	30.5	31.2	28.5	29.8	29.7
630	57.0	31.2	32.8	33.0	29.8	31.6
800	58.9	28.1	31.9	27.4	29.1	29.1
1000	62.9	30.7	31.9	30.7	30.9	31.1
1250	66.2	31.0	30.7	31.4	30.7	30.9
1600	68.0	32.5	33.8	32.2	32.8	32.9
2000	67.5	37.7	36.7	36.5	35.7	36.3
2500	63.0	40.0	38.2	38.5	37.8	38.2
3150	57.5	-	-	-	-	-
4000	51.2	-	-	-	-	-

Table B8. Noise Intrusion Reduction, Data Set No.1, Test House No.8

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	55.9	15.1	18.1	15.9	11.9	14.5
63	64.7	14.9	26.1	22.0	15.2	18.9
80	63.8	14.7	11.8	11.3	22.8	13.1
100	64.4	16.1	14.4	12.1	13.6	13.3
125	69.4	17.8	20.6	18.4	19.2	19.3
160	66.1	17.5	17.9	20.4	26.6	20.4
200	63.6	19.3	24.6	27.1	31.1	26.9
250	64.5	20.2	26.5	25.5	26.0	26.0
315	72.7	27.9	25.9	29.0	31.5	28.2
400	63.4	24.4	23.2	23.1	25.2	23.7
500	62.5	27.5	30.3	24.0	30.0	27.1
630	63.2	27.2	30.7	32.7	30.7	31.3
800	64.9	29.9	32.9	28.2	31.4	30.4
1000	67.8	29.5	32.3	30.1	33.3	31.7
1250	67.0	28.7	31.0	28.3	30.8	29.9
1600	66.0	25.4	29.0	28.7	29.2	29.0
2000	62.4	24.6	27.9	27.9	28.6	28.1
2500	60.4	31.8	33.2	29.7	31.4	31.2
3150	58.5	33.5	34.7	32.2	32.7	33.1
4000	55.9	32.9	-	32.6	-	-

Table B9. Noise Intrusion Reduction, Data Set No.1, Test House No.8, 2.8 Seconds Before Maximum Interior A-Weighted Sound Level

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	52.9	13.3	9.7	7.9	7.7	8.3
63	51.4	23.7	18.9	15.7	11.9	14.6
80	60.4	22.9	16.9	20.1	11.6	14.8
100	63.1	22.3	12.9	14.8	27.3	15.4
125	67.7	16.4	14.5	9.7	14.5	12.3
160	63.4	19.8	19.6	15.4	22.4	18.2
200	56.4	21.8	16.4	19.9	17.2	17.6
250	65.0	28.4	25.0	27.7	24.2	25.4
315	54.1	24.3	24.1	25.4	23.1	24.1
400	48.9	22.3	25.1	23.4	24.7	24.3
500	49.4	22.1	22.4	25.4	26.6	24.4
630	50.8	24.0	26.0	26.1	26.8	26.3
800	48.8	24.0	26.3	23.5	23.3	24.2
1000	50.1	25.1	26.6	25.6	25.1	25.7
1250	52.2	25.9	26.7	27.2	26.4	26.8
1600	53.8	23.0	26.0	25.1	26.0	25.7
2000	52.3	24.3	27.1	26.8	26.3	26.7
2500	51.8	25.5	27.1	27.3	26.6	27.0
3150	50.7	27.4	-	27.2	27.7	27.5
4000	48.3	-	25.1	22.6	20.1	21.3

Table B10. Noise Intrusion Reduction, Data Test No.1, Test House No.8, 1.4 Seconds Before Maximum Interior A-Weighted Sound Level

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	54.7	17.3	16.3	9.7	11.0	11.5
63	61.1	20.6	23.5	10.1	18.9	14.2
80	65.8	25.7	8.0	13.5	19.3	11.5
100	62.9	17.6	7.9	15.2	17.4	11.5
125	70.3	16.7	12.1	24.0	18.8	15.8
160	74.2	24.2	20.4	19.9	19.0	19.7
200	62.4	21.8	27.6	14.4	19.4	17.8
250	63.9	21.9	28.4	24.9	26.1	26.2
315	68.9	27.1	26.9	25.9	28.7	27.0
400	58.1	26.5	28.6	27.8	27.3	27.9
500	57.5	25.5	26.0	28.8	30.3	28.0
630	59.3	30.7	31.3	31.8	32.3	31.8
800	57.0	29.7	29.8	29.0	30.2	29.6
1000	58.4	27.4	27.9	28.1	28.2	28.1
1250	60.1	25.1	29.9	30.1	28.6	29.5
1600	62.0	25.4	30.0	28.7	30.0	29.5
2000	59.4	26.1	27.9	29.4	29.6	28.9
2500	58.0	30.2	29.8	28.0	29.8	29.1
3150	57.5	33.2	34.3	31.5	32.5	32.6
4000	56.0	33.0	33.8	32.3	33.2	33.1

Table B11. Noise Intrusion Reduction, Data Set No.1, Test House No.8, 1.4 Seconds After Maximum Interior Sound Level

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	61.3	11.7	19.8	16.8	14.8	16.7
63	66.1	11.1	21.6	15.1	14.3	16.0
80	59.5	17.7	16.3	12.8	19.0	15.3
100	66.7	17.4	21.7	22.2	29.4	23.3
125	72.4	17.1	21.6	31.4	30.4	25.4
160	68.9	16.9	20.4	25.4	25.9	23.1
200	62.6	17.8	21.6	25.6	26.8	24.1
250	65.7	23.7	25.2	27.2	29.9	27.0
315	66.1	25.1	28.1	27.8	33.6	29.2
400	59.9	25.9	29.1	30.6	31.1	30.2
500	54.8	25.8	25.3	27.5	25.8	26.1
630	62.4	35.6	36.6	31.1	35.4	33.7
800	61.5	29.7	33.0	33.5	34.0	33.5
1000	67.7	28.9	33.2	34.2	34.7	34.0
1250	70.1	28.5	32.3	34.8	35.6	34.0
1600	70.4	29.4	32.9	34.4	35.4	34.1
2000	69.7	29.9	34.2	37.4	38.5	36.3
2500	66.9	35.6	38.4	39.9	39.7	39.3
3150	62.7	36.1	37.7	38.4	38.9	38.3
4000	58.4	34.6	-	-	-	-

Table B12. Noise Intrusion Reduction, Data Set No.1, Test House No.8, 2.8 Seconds After Maximum A-Weighted Interior Sound Level

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	64.7	24.1	19.7	17.2	24.7	19.6
63	66.6	23.8	28.3	18.3	-	20.9
80	63.0	18.0	4.0	6.7	21.0	6.8
100	66.4	21.6	12.6	19.4	23.4	16.3
125	69.3	22.3	14.1	24.8	23.3	18.1
160	69.9	21.9	19.9	25.4	21.7	21.8
200	67.6	25.0	25.2	26.1	29.6	26.6
250	71.2	23.6	26.7	25.7	32.7	27.5
315	65.3	19.0	24.1	25.6	26.1	25.2
400	59.7	25.1	26.5	29.7	29.7	28.4
500	54.8	25.2	29.6	28.3	29.0	28.9
630	57.9	29.1	31.9	32.2	32.4	32.2
800	58.6	25.0	29.1	31.3	32.6	30.8
1000	60.0	25.7	30.2	29.3	30.8	30.1
1250	59.8	25.8	29.3	30.8	28.8	29.6
1600	61.1	27.5	30.8	30.4	32.6	31.2
2000	59.0	26.4	30.0	32.5	32.8	31.6
2500	58.2	30.9	32.4	32.5	34.0	32.9
3150	55.4	30.6	32.2	32.1	32.2	32.2
4000	51.2	26.9	-	-	-	-

Table B13. Noise Intrusion Reduction, Data Set No.1, Test House No.9, Passby No.1

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	68.5	14.5	19.3	9.7	18.8	13.6
63	63.8	13.5	16.9	11.8	20.6	15.0
80	68.5	18.0	11.1	13.0	16.1	12.9
100	72.3	17.0	21.6	16.8	16.6	17.8
125	70.3	23.8	26.6	24.5	19.9	22.7
160	69.3	16.3	17.1	16.3	25.6	18.2
200	72.3	16.8	19.1	28.3	26.4	22.7
250	71.7	19.7	24.7	31.2	30.3	27.7
315	70.2	20.7	28.4	29.4	24.2	26.7
400	72.1	21.8	29.7	28.3	24.4	26.9
500	70.3	27.6	30.6	30.1	24.9	27.7
630	68.1	28.8	33.9	33.1	30.9	32.4
800	74.2	31.9	34.0	33.7	33.2	33.6
1000	80.8	32.8	36.1	34.3	32.4	34.0
1250	83.3	38.0	39.6	37.3	36.1	37.4
1600	83.1	38.6	38.1	39.3	37.7	38.3
2000	82.8	40.5	40.6	42.0	41.1	41.2
2500	75.6	38.1	37.9	39.4	37.2	38.1
3150	70.0	35.0	35.0	35.2	33.8	34.6
4000	68.4	37.7	38.4	39.2	37.2	38.2

Table B14. Noise Intrusion Reduction, Data Set No.1, Test House No.9, Passby No.2

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	64.0	20.3	20.3	11.5	17.8	14.9
63	68.2	16.5	15.0	15.2	23.8	16.6
80	72.5	20.8	17.8	19.3	21.5	19.3
100	71.2	24.9	24.8	24.7	24.0	24.5
125	81.8	27.5	27.1	30.6	25.8	27.4
160	70.9	19.4	22.2	25.1	26.9	24.3
200	69.9	20.4	18.9	24.4	29.9	22.3
250	68.2	23.5	23.2	26.4	24.8	24.6
315	67.7	21.2	24.5	27.9	22.3	24.3
400	70.9	22.9	28.2	27.9	22.7	25.5
500	69.9	26.4	27.2	28.1	21.5	24.5
630	64.4	27.9	30.2	30.9	29.2	30.1
800	72.5	29.1	31.8	32.0	30.8	31.5
1000	79.5	30.0	31.8	31.3	30.3	31.1
1250	80.7	34.2	36.7	35.2	33.5	34.9
1600	77.4	36.7	35.4	36.6	35.2	35.7
2000	74.8	37.8	37.1	39.3	37.1	37.7
2500	70.3	37.0	36.9	38.3	34.3	36.2
3150	64.9	33.4	34.9	36.4	30.5	33.2
4000	64.6	35.9	37.2	37.8	-	37.5

Table B15. Noise Intrusion Reduction, Data Set No.1, No.9, Passby No.3

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	70.0	16.0	24.6	7.2	16.3	11.4
63	68.8	15.8	13.8	13.8	26.1	15.4
80	74.1	19.4	16.9	17.9	18.1	17.6
100	70.9	21.6	17.9	18.7	17.9	18.2
125	77.8	22.5	24.1	24.0	25.6	24.5
160	73.2	18.9	22.0	21.0	25.2	22.4
200	71.5	21.0	16.3	22.5	24.5	19.6
250	69.9	20.6	19.9	26.4	25.2	22.9
315	70.4	22.7	22.7	29.9	23.0	24.2
400	71.8	25.8	28.6	30.8	24.1	26.9
500	69.3	28.3	27.9	28.3	21.6	24.8
630	65.9	27.6	31.7	30.9	30.7	31.1
800	73.6	29.9	32.9	33.6	30.6	32.2
1000	78.3	29.8	33.3	30.8	28.1	30.2
1250	82.9	36.6	37.2	34.7	33.7	35.0
1600	80.2	35.2	35.8	38.2	35.0	36.1
2000	78.3	35.3	38.1	39.5	38.1	38.5
2500	73.6	35.3	37.6	39.1	35.6	37.2
3150	67.4	30.1	34.7	35.6	31.4	33.5
4000	66.5	35.0	37.5	38.3	-	37.9

Table B16. Noise Intrusion Reduction, Data Set No.1, Test House No.9, Passby No.4

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	65.1	21.1	19.7	11.1	17.7	14.5
63	68.6	16.6	16.4	16.1	22.6	17.5
80	76.5	22.8	20.1	18.5	21.8	19.9
100	74.7	28.7	26.3	26.7	22.7	24.8
125	88.8	26.3	29.8	36.3	27.4	29.9
160	75.2	23.2	25.2	25.7	28.0	26.1
200	72.1	22.4	18.9	26.9	24.1	22.0
250	72.0	24.0	22.0	32.0	26.8	25.2
315	72.7	21.2	28.7	33.2	29.3	30.0
400	69.5	21.5	27.8	28.7	23.5	26.0
500	70.7	27.4	29.5	30.2	23.3	26.5
630	67.0	30.3	33.0	31.0	32.0	31.9
800	72.8	30.5	33.6	33.3	32.8	33.2
1000	81.0	30.7	35.0	33.0	29.8	32.1
1250	81.0	36.5	37.0	34.8	31.8	34.0
1600	79.8	37.8	35.6	36.8	34.6	35.6
2000	79.8	39.8	39.4	40.3	38.6	39.4
2500	72.3	37.6	36.9	38.5	34.1	36.1
3150	67.8	34.1	35.4	35.3	31.6	33.7
4000	66.0	36.5	37.8	39.2	-	38.4

B17. Noise Intrusion Reduction, Data Set No.1, Test House No.9, Passby No.5

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	65.9	18.9	20.9	9.9	17.5	13.7
63	68.1	16.6	15.7	14.3	22.9	16.4
80	71.2	16.5	16.0	18.7	20.5	18.0
100	70.4	16.9	17.7	20.9	19.2	19.1
125	72.9	26.2	25.9	23.4	24.5	24.5
160	74.5	20.2	22.8	23.7	25.5	23.9
200	72.4	21.7	16.2	27.4	28.2	20.4
250	71.7	23.2	23.5	26.7	23.3	24.2
315	71.7	21.4	25.7	31.6	23.9	26.0
400	71.8	21.5	28.6	30.3	24.6	27.2
500	71.1	28.6	26.9	32.1	22.4	25.5
630	64.7	28.0	29.5	29.5	28.5	29.1
800	71.6	30.9	32.2	33.6	30.4	31.9
1000	78.5	32.2	34.5	32.3	30.8	32.3
1250	82.5	36.2	39.8	38.0	35.8	37.6
1600	82.6	38.3	39.9	39.4	39.9	39.7
2000	81.1	39.1	40.9	41.6	41.9	41.4
2500	75.3	38.3	41.3	40.1	38.6	39.9
3150	71.5	36.8	41.3	37.7	35.5	37.6
4000	68.5	38.5	41.1	39.3	-	40.1

Table B18. Noise Intrusion Reduction, Data Set No.1, Test House No.9, Front Door Open

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	64.9	5.9	4.9	4.9	7.9	6.7
63	65.1	7.4	8.4	9.9	12.4	9.9
80	64.3	12.8	6.9	7.5	12.1	7.4
100	74.1	17.1	10.1	9.6	11.9	10.4
125	77.3	14.8	25.9	19.8	15.3	18.5
160	73.4	3.1	17.0	6.2	12.4	9.8
200	77.1	17.8	15.4	22.1	19.4	18.1
250	65.7	17.0	10.7	13.5	14.7	12.6
315	68.6	17.6	14.9	14.6	19.6	15.9
400	72.0	18.5	16.8	14.8	20.8	16.8
500	69.7	17.0	15.7	14.2	17.5	15.6
630	66.8	14.8	12.1	13.0	17.6	13.7
800	75.2	13.7	15.8	15.4	20.2	16.7
1000	78.2	15.2	14.5	12.0	16.0	13.8
1250	80.8	13.8	12.4	10.8	16.1	12.6
1600	83.3	13.0	13.1	10.8	16.6	12.9
2000	77.7	10.7	10.7	7.5	14.0	10.0
2500	74.7	10.2	9.5	8.5	12.7	9.9
3150	69.7	8.4	11.5	7.9	13.5	10.3
4000	65.1	7.8	11.9	9.1	13.7	11.1

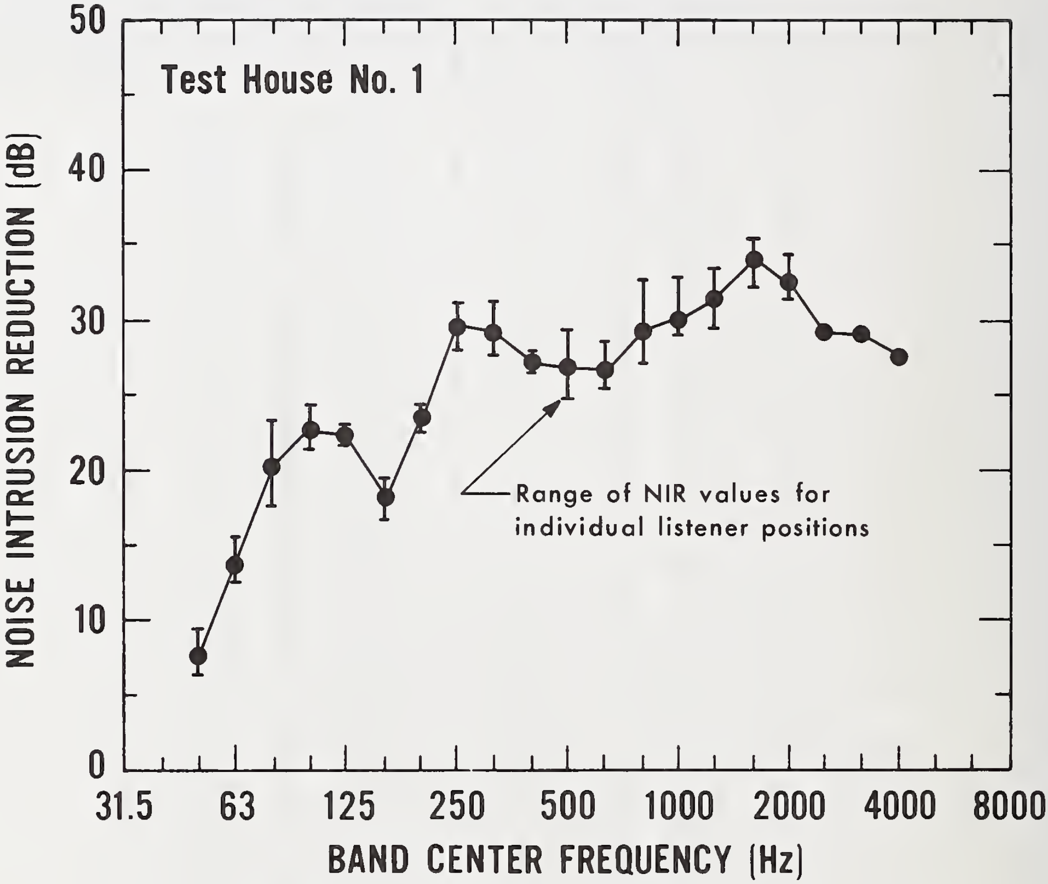

Figure B1. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 1, Data Set No. 1.

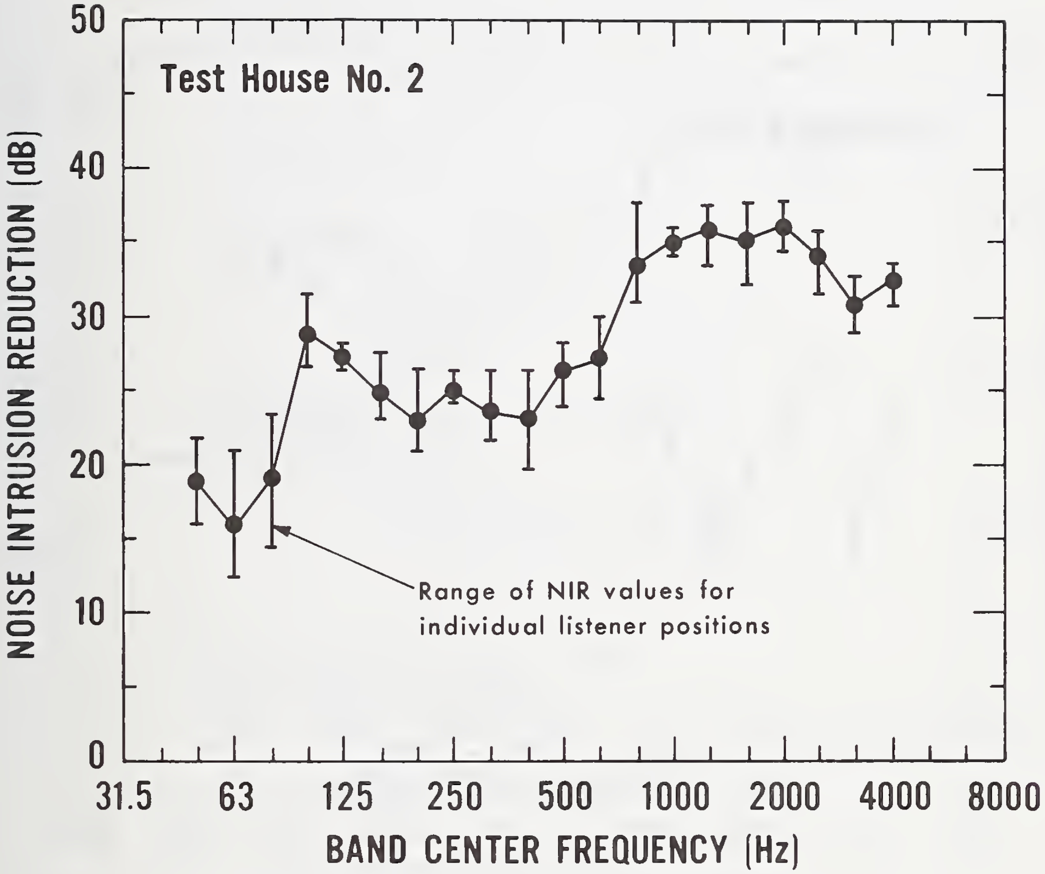

Figure B2. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 2, Data Set No. 1.

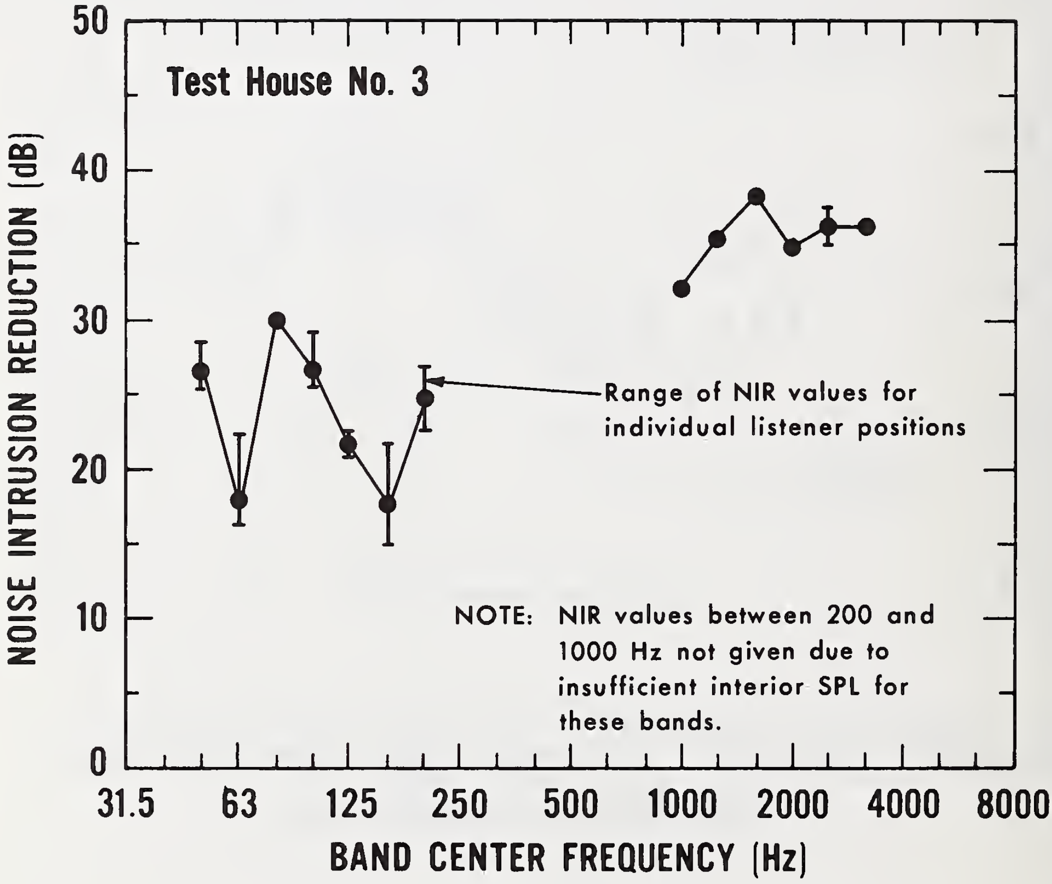

Figure B3. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 3, Data Set No. 1.

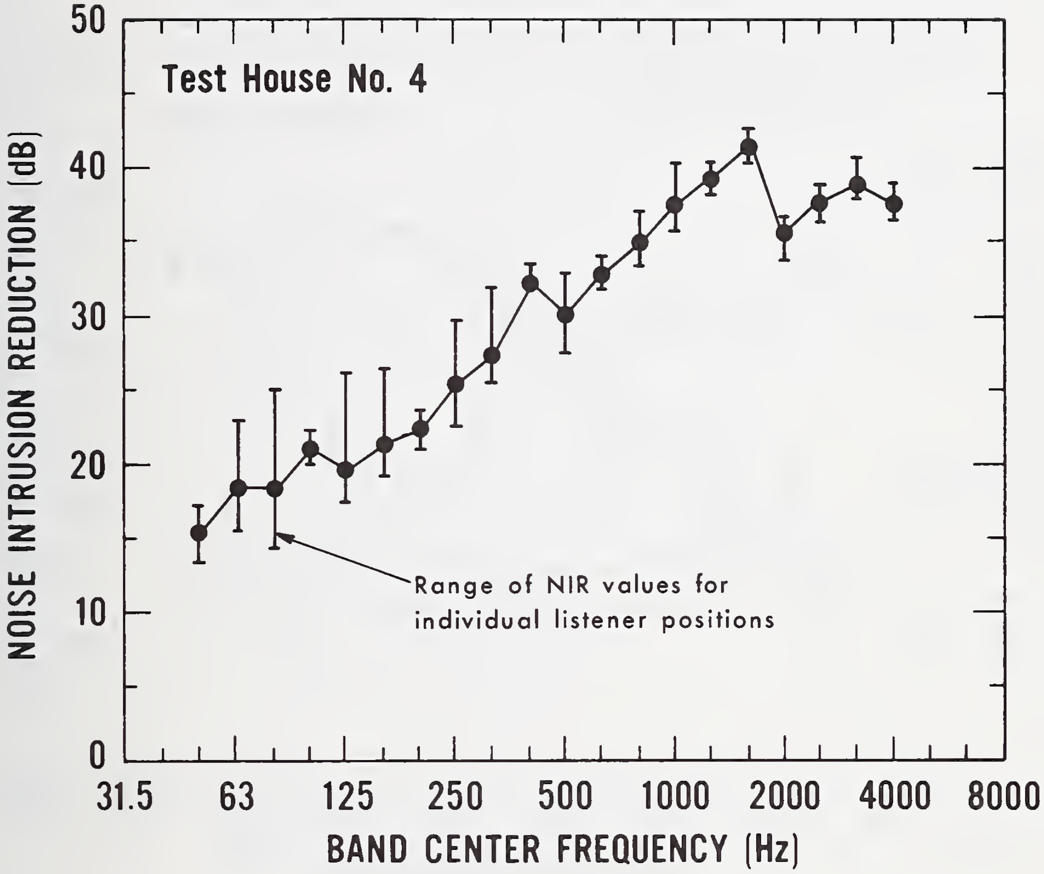

Figure B4. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 4, Data Set No. 1.

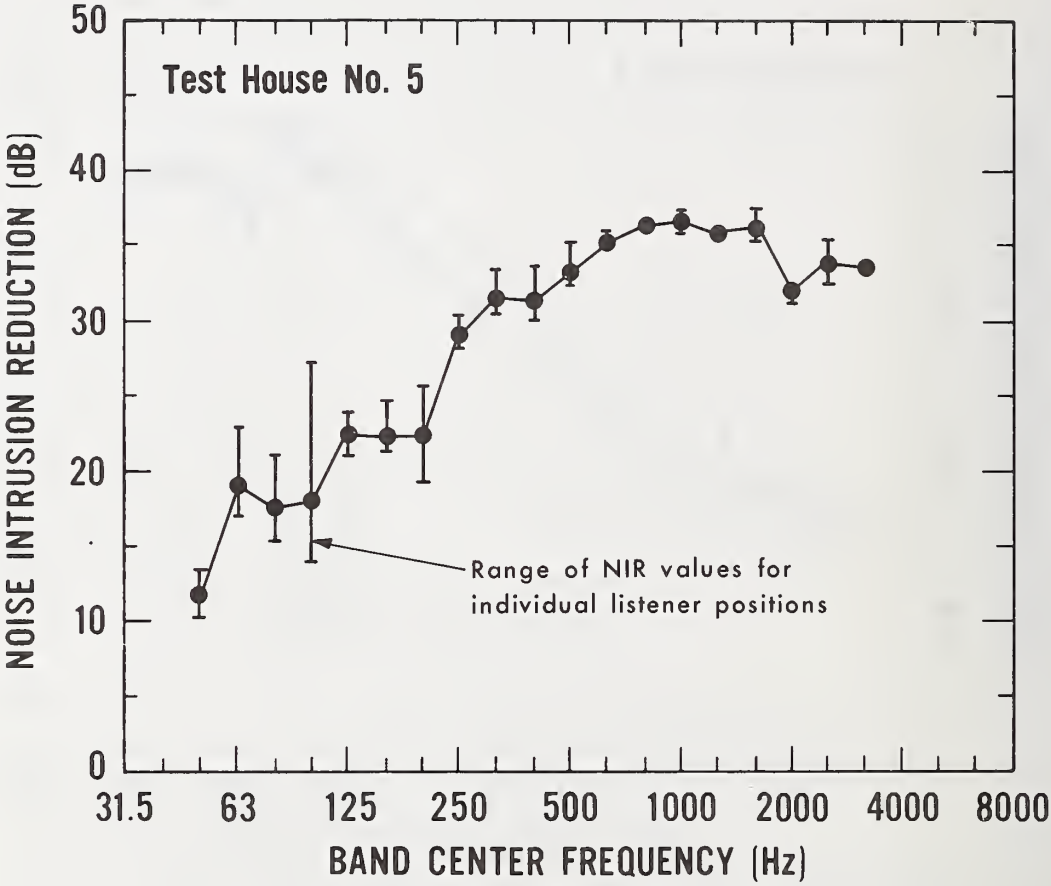

Figure B5. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 5, Data Set No. 1.

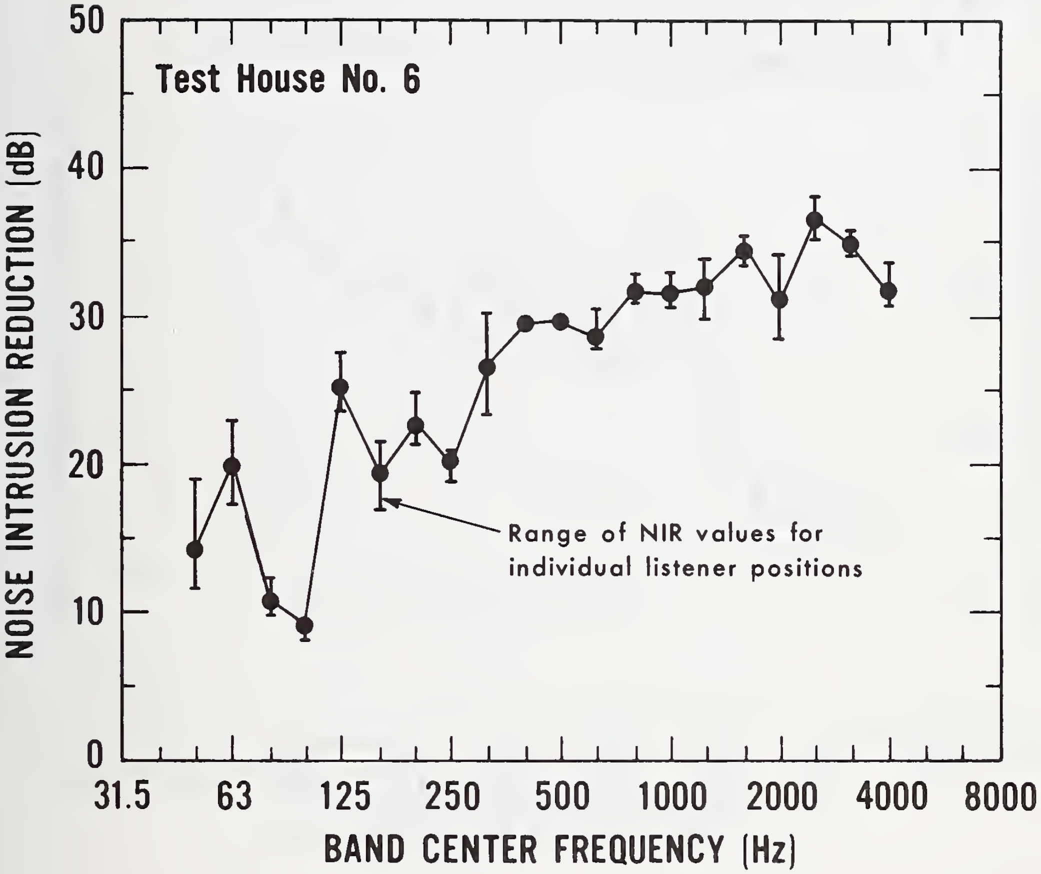

Figure B6. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 6, Data Set No. 1.

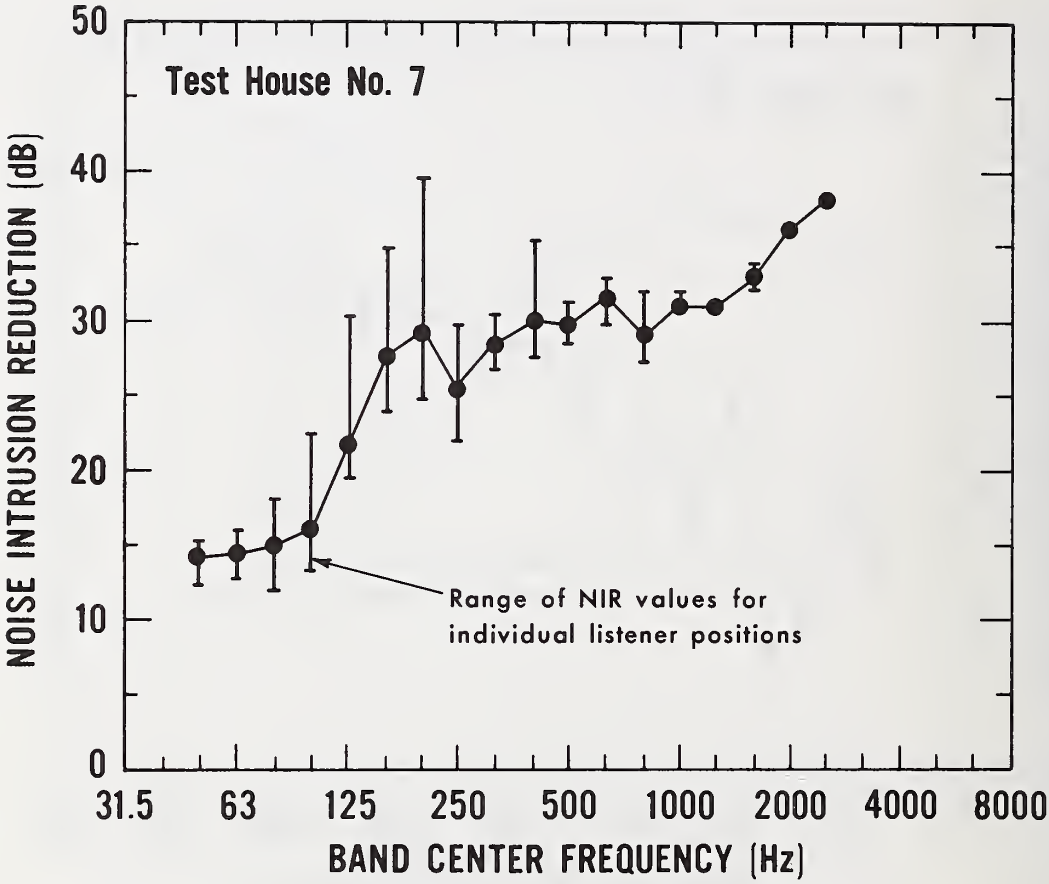

Figure B7. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 7, Data Set No. 1.

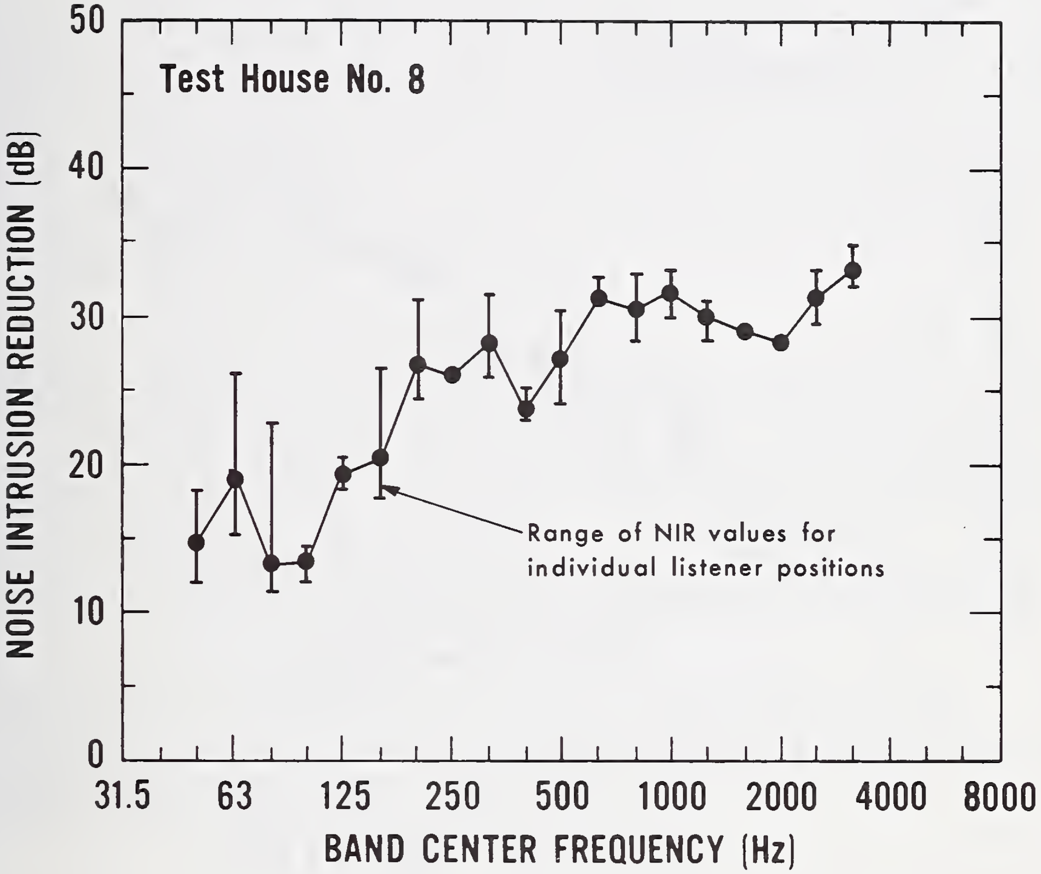

Figure B8. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 8, Data Set No. 1.

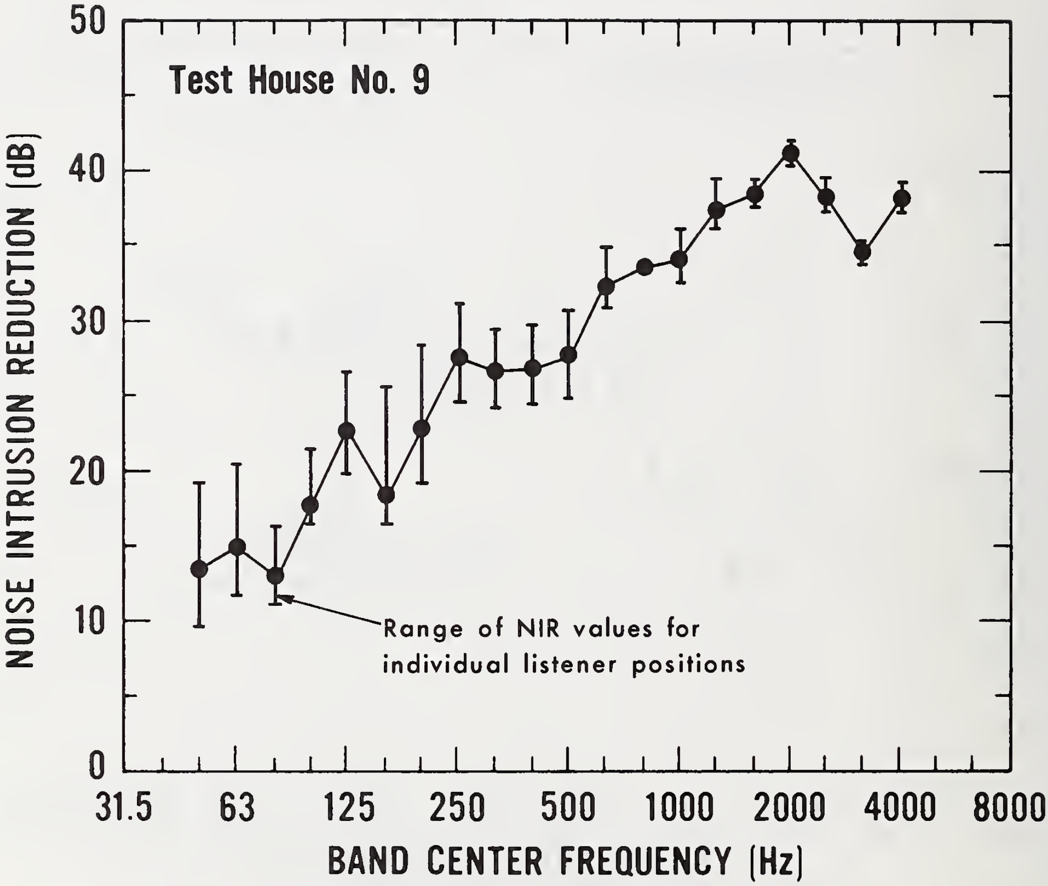

Figure B9. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 9, Data Set No. 1.

Appendix C. Values of Noise Intrusion Reduction Determined With Maximum Occurring Outdoor and Indoor Sound Pressure Levels

The NIR values presented in this Appendix were obtained from the maximum sound pressure levels measured at each exterior and interior microphone position regardless of when, during the test vehicle passby, the maximum level at an individual position occurred. These values of NIR correspond to those of Data Set No. 2 as referred to in Section 3.3. The 1/3-octave band values of NIR from 50 to 4000 Hz obtained using this data reduction technique are presented in Tables C1 through C19. In Tables C1-C18, the average of the two 3-m exterior sound pressure levels are presented along with the NIR values for the interior reference microphone position, those for the three individual listener microphone positions, and the average of the listener position values, as determined using Eq. (4) of Section 4.1.1.

The NIR values used to obtain the average NIR for the nine test houses are presented in Tables C1, C3, and C7-C13. Additional NIR values for three different test vehicle passbys of test house No. 2 are presented in Tables C2, C4, and C5. Also, NIR values for four additional passbys of Test House No. 9 are presented in Tables C14-C17. NIR values determined with the windows open for Test House No. 2 are given in Table C6 and values with the front door of Test House No. 9 open are given in Table C18. A summary of the NIR values averaged over the three listener positions for each of the nine test houses is presented in Table C19, along with NIR values averaged for all nine houses, using Eq. (7) of Section 4.2.1 (for both 1/3- and 1/1-octave bands).

Also included in this Appendix are plots of the average NIR values determined for each of the nine test houses with windows and doors closed. These are presented in Figures C1-C9 and correspond to the values in Tables C1, C3, and C7-C13.

Table C1. Noise Intrusion Reduction, Data Set No.2, Test House No.1

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	70.3	16.3	11.8	13.3	16.2	13.4
63	71.0	15.4	18.8	13.0	14.7	14.9
80	64.5	18.1	23.2	17.5	18.8	19.2
100	67.3	23.2	24.4	21.6	24.0	23.1
125	73.1	23.7	29.4	24.6	31.3	27.5
160	66.1	23.0	22.7	17.9	20.6	20.0
200	67.6	26.4	25.6	22.0	25.0	23.9
250	74.9	23.4	30.3	26.9	32.8	29.3
315	70.7	27.1	28.7	26.3	30.1	28.1
400	62.6	29.2	27.0	26.1	27.6	26.9
500	69.6	30.6	34.4	29.6	29.6	30.7
630	67.4	30.6	33.3	29.6	31.2	31.1
800	66.2	33.1	35.1	31.0	32.6	32.6
1000	65.2	32.3	35.4	31.3	30.6	32.0
1250	65.8	32.0	35.7	30.6	32.4	32.4
1600	63.8	34.5	37.1	32.3	33.9	34.0
2000	61.6	34.1	38.1	31.5	32.8	35.1
2500	59.4	34.5	37.5	31.4	32.6	34.7
3150	55.7	35.5	36.0	32.1	31.5	33.7
4000	53.4	34.8	34.8	30.0	30.4	32.3

Table C2. Noise Intrusion Reduction, Data Set No.2, Test House No.2, Passby No.1

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB: Interior Reference Position	NIR, dB: Listener Position No.1	NIR, dB: Listener Position No.2	NIR, dB: Listener Position No.3	NIR, dB: Average of Listener Positions
Frequency	AVG	NR	NR	NR	NR	NR
50	62.0	-	-	-	-	-
63	67.6	11.1	14.1	12.3	12.9	13.0
80	70.4	19.0	23.8	14.8	16.9	17.2
100	76.5	23.7	24.0	14.9	21.2	18.3
125	80.2	18.6	18.7	26.8	22.8	21.6
160	81.5	19.4	17.8	29.8	22.0	21.0
200	73.9	19.4	22.5	27.9	28.6	25.4
250	65.4	17.3	24.0	24.8	22.3	23.6
315	59.6	16.3	21.5	23.8	20.5	21.7
400	57.4	21.0	25.6	27.4	24.7	25.8
500	59.0	25.8	27.2	28.6	26.3	27.3
630	60.0	26.9	27.0	29.5	27.9	28.0
800	64.0	28.6	33.1	33.3	31.9	32.7
1000	68.9	33.9	33.7	36.0	34.4	34.6
1250	71.2	34.4	35.4	37.7	37.9	36.8
1600	69.9	34.4	34.1	37.2	37.2	35.9
2000	70.9	35.1	33.7	38.2	37.4	36.0
2500	69.9	34.9	32.1	38.8	37.8	35.2
3150	65.3	32.8	32.8	34.6	35.7	34.2
4000	64.0	36.9	37.1	38.7	38.4	38.0

Table C3. Noise Intrusion Reduction, Data Set No.2, Test House No.2
Passby No.2

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
Frequency	AVG	NR	NR	NR	NR	NR
50	68.4	13.1	16.5	16.7	14.7	15.9
63	64.4	11.8	15.2	15.5	13.0	14.4
80	74.6	22.8	21.7	17.1	20.0	19.2
100	73.1	25.1	28.5	20.8	24.8	23.6
125	81.7	29.5	26.1	33.6	28.2	28.3
160	71.2	20.2	21.0	26.0	25.0	23.4
200	77.3	19.7	25.4	25.9	30.2	26.7
250	70.8	22.7	26.4	25.6	25.6	25.9
315	62.7	21.0	23.4	26.9	23.8	24.4
400	59.6	21.0	23.6	27.0	25.4	25.1
500	62.1	25.7	26.3	29.1	25.3	26.6
630	61.4	26.9	28.9	29.1	29.1	29.0
800	65.5	28.3	32.7	32.4	31.5	32.2
1000	69.6	34.2	34.6	35.8	35.4	35.2
1250	71.2	34.3	35.3	37.5	37.6	36.7
1600	70.5	33.8	35.1	37.5	37.2	36.5
2000	70.7	34.1	33.4	38.1	37.1	35.7
2500	70.3	35.1	33.9	37.7	37.8	36.1
3150	65.0	33.0	32.8	33.7	34.4	33.6
4000	63.8	36.1	36.3	38.8	37.9	37.5

Table C4. Noise Intrusion Reduction, Data Set No.2, Test House No.2, Passby No. 4

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	68.6	13.8	11.3	16.6	15.0	13.7
63	65.8	12.5	11.3	15.1	14.2	13.2
80	72.4	21.0	22.0	14.0	18.8	17.0
100	74.5	30.5	28.6	23.5	25.2	25.3
125	76.9	20.2	19.9	30.6	26.2	23.5
160	74.4	19.8	20.4	28.9	24.6	23.3
200	76.4	21.2	24.6	25.1	29.0	25.8
250	72.3	19.9	24.5	25.8	23.3	24.4
315	66.4	19.4	21.6	27.2	23.1	23.4
400	64.5	22.7	24.8	26.4	26.6	25.9
500	63.8	26.2	27.3	28.2	26.9	27.4
630	63.1	26.9	28.9	29.4	28.5	28.9
800	66.6	28.1	33.1	33.7	32.5	33.1
1000	70.1	33.7	34.3	35.5	35.2	35.0
1250	70.9	34.4	34.9	37.2	37.5	36.4
1600	69.6	34.0	33.8	37.4	36.8	35.7
2000	70.4	35.3	34.0	38.9	38.2	36.5
2500	69.2	35.4	34.1	37.1	37.7	36.0
3150	64.2	31.1	31.0	31.2	31.1	31.7
4000	63.0	35.5	35.8	38.1	37.2	36.9

Table C5. Noise Intrusion Reduction, Data Set No.2, Test House No.2
Passby No.4

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	64.7	11.5	11.8	13.0	12.4	12.4
63	63.7	11.6	11.9	16.6	12.6	13.3
80	69.2	18.6	20.3	12.2	17.1	15.3
.00	73.7	31.1	28.1	19.3	26.9	22.9
125	73.9	19.9	19.6	27.8	23.7	22.5
160	75.6	16.7	16.6	27.3	21.1	19.8
200	74.9	19.6	25.0	24.5	28.4	25.7
250	73.1	20.6	25.7	25.7	24.2	25.1
315	68.3	23.2	23.7	26.6	23.8	24.5
400	63.4	23.4	26.6	28.0	26.9	27.1
500	63.6	26.0	25.8	28.7	25.4	26.4
630	63.7	27.3	28.9	30.4	28.4	29.2
800	65.9	29.1	32.0	32.8	31.7	32.1
1000	69.5	33.3	34.1	35.0	35.0	34.7
1250	70.9	34.7	35.1	37.9	37.1	36.5
1600	69.3	33.5	33.8	37.0	36.6	35.6
2000	69.4	34.1	32.6	37.6	36.6	35.0
2500	69.3	35.0	32.9	38.3	37.7	35.6
3150	64.3	32.4	32.4	34.1	34.3	33.5
4000	63.1	35.7	36.1	38.4	37.9	37.4

Table C6. Noise Intrusion Reduction, Data Set No.2, Test House No.2
Windows Open

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	66.3	9.9	13.5	16.5	12.7	14.0
63	64.2	8.7	12.8	14.2	9.0	11.4
80	69.6	13.7	18.8	11.2	13.1	13.4
100	67.8	17.7	18.6	13.5	15.2	15.3
125	72.2	13.6	12.0	19.4	16.2	14.8
160	73.3	10.5	10.7	19.8	13.6	13.3
200	74.8	14.6	17.2	18.7	20.6	18.6
250	70.1	10.9	14.4	15.3	10.6	12.9
315	65.0	11.3	13.6	14.3	15.3	14.3
400	63.3	10.8	13.0	12.8	13.8	13.2
500	63.8	7.2	13.9	14.5	12.9	13.7
630	62.5	6.5	11.9	13.7	14.0	13.1
800	65.9	6.8	13.0	13.9	13.2	13.3
1000	71.1	7.3	14.5	16.4	12.4	14.1
1250	74.7	5.7	14.8	15.7	12.2	14.0
1600	74.0	5.3	14.0	15.7	10.8	13.0
2000	67.5	5.8	12.5	14.7	7.6	10.6
2500	67.4	6.9	12.5	15.3	7.2	10.4
3150	66.5	5.1	16.9	19.1	9.8	13.3
4000	63.4	3.9	16.2	17.7	11.8	14.5

Table C7. Noise Intrusion Reduction, Data Set No.2, Test House No.3

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
63	56.0	8.8	16.7	10.8	11.9	12.5
63	64.9	22.6	23.8	21.6	22.7	22.6
80	66.4	22.4	27.4	25.1	25.7	26.0
100	72.4	26.8	25.8	26.8	26.2	26.2
125	74.6	30.2	21.9	29.0	26.7	24.8
160	77.2	21.6	23.3	25.3	24.7	24.4
200	72.6	20.2	28.4	28.7	24.9	27.0
250	72.7	27.1	37.2	33.2	31.7	33.5
315	60.2	21.8	31.6	30.7	30.0	30.7
400	55.4	26.2	28.5	30.8	29.0	29.3
500	55.2	27.8	30.8	32.2	29.9	30.9
630	52.9	29.8	30.9	31.7	28.9	30.3
800	52.6	29.6	31.4	32.2	31.2	31.6
1000	58.4	33.2	33.3	35.0	34.2	34.1
1250	63.0	36.2	36.8	34.6	36.6	35.9
1600	65.6	37.8	38.8	39.2	39.1	39.0
2000	65.9	32.6	33.0	34.3	34.9	34.0
2500	66.9	35.7	35.8	36.5	37.9	36.6
3150	65.3	37.7	37.6	38.2	38.6	38.1
4000	62.7	38.4	38.5	40.0	39.0	39.1

Table C8. Noise Intrusion Reduction, Data Set No. 2, Test House No. 4

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	68.4	14.0	13.8	8.7	14.6	11.5
63	64.4	15.2	17.8	11.3	23.1	15.0
80	76.9	21.1	19.8	17.9	25.1	20.0
100	68.1	20.4	22.0	18.4	17.5	18.9
125	81.2	22.1	25.6	22.4	18.8	21.4
160	70.9	19.8	29.5	24.9	20.9	23.8
200	76.8	20.7	28.1	26.8	22.3	25.0
250	72.7	21.5	31.4	31.7	26.7	29.3
315	66.7	19.3	26.4	31.0	28.0	28.1
400	67.1	24.2	30.1	33.1	30.7	31.1
500	64.2	25.8	32.3	28.2	30.8	30.1
630	63.5	29.2	35.0	33.0	33.2	33.6
800	67.5	31.4	36.8	34.9	35.2	35.6
1000	71.0	32.1	39.7	37.2	38.0	38.2
1250	73.7	33.6	40.8	38.2	39.4	39.3
1600	72.0	34.9	42.4	38.9	40.4	40.3
2000	68.7	33.6	38.4	36.0	36.0	36.7
2500	69.0	33.8	39.6	38.4	37.5	38.4
3150	67.5	35.8	42.0	38.9	38.7	39.6
4000	63.9	34.1	39.9	37.9	37.1	38.1

Table C9. Noise Intrusion Reduction, Data Set No. 2, Test House No. 5

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	70.9	10.3	13.4	11.0	9.3	10.9
63	7.15	13.5	9.5	13.7	17.2	12.4
80	67.0	16.8	21.1	14.2	13.3	15.1
100	76.7	18.9	25.0	9.3	23.5	13.8
125	63.9	15.4	17.9	15.6	15.0	16.0
160	68.5	14.2	17.3	22.0	23.6	20.1
200	73.5	22.3	22.0	26.1	22.0	23.0
250	65.9	29.9	26.9	28.8	31.8	28.7
315	64.6	28.2	29.9	28.8	31.3	29.9
400	62.9	26.9	29.7	31.7	28.7	29.9
500	60.6	28.9	30.3	31.2	30.6	30.7
630	61.8	32.0	33.9	32.2	32.3	32.7
800	64.4	36.4	36.2	36.1	37.3	36.5
1000	69.9	36.8	38.4	38.6	38.7	38.5
1250	72.6	35.2	37.4	36.8	37.0	37.1
1600	71.1	37.0	39.0	37.1	36.5	37.4
2000	69.5	35.0	36.9	35.9	35.7	36.1
2500	70.1	37.7	39.4	38.2	37.1	38.1
3150	66.7	38.3	38.8	38.9	38.3	38.7
4000	63.8	39.0	39.8	39.6	40.2	39.9

Table C10. Noise Intrusion Reduction, Data Set No. 2, Test House No. 6

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	67.6	12.2	13.2	19.4	11.6	13.7
63	67.1	19.1	17.6	22.4	16.2	18.0
80	73.8	15.3	16.8	16.0	19.6	17.2
100	71.2	15.7	17.7	16.8	19.4	17.8
125	75.9	20.9	21.9	17.0	24.1	20.0
160	74.3	23.1	19.8	20.8	25.2	21.4
200	70.8	20.3	22.4	23.3	27.8	23.9
250	66.4	21.3	34.2	25.2	24.8	24.7
315	65.7	21.7	24.7	25.0	24.7	24.8
400	61.7	25.8	25.0	26.9	26.1	25.9
500	58.5	23.5	20.5	24.1	25.2	22.8
630	57.7	26.9	24.6	27.2	25.7	25.7
800	61.2	29.7	29.7	30.6	30.6	30.6
1000	64.4	30.5	31.6	30.4	33.1	31.6
1250	68.2	30.9	34.2	30.0	33.9	32.2
1600	70.5	34.1	35.4	33.2	36.4	34.8
2000	70.3	32.9	34.0	27.3	35.6	30.7
2500	70.0	35.1	38.0	36.2	38.3	37.4
3150	67.4	30.5	37.3	37.4	37.6	37.4
4000	62.8	32.7	34.2	34.1	36.6	34.8

Table C11. Noise Intrusion Reduction, Data Set No. 2, Test House No. 7

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	69.6	13.8	13.4	14.5	16.0	14.5
63	72.2	13.5	13.0	16.5	14.9	14.6
80	70.5	15.0	17.9	16.6	21.2	18.2
100	75.8	17.3	17.8	15.3	22.9	17.7
125	66.2	25.2	31.3	19.8	19.9	21.5
160	68.3	19.3	23.4	26.4	24.0	24.4
200	75.6	26.3	32.9	34.9	25.6	29.2
250	65.9	20.5	27.5	23.5	26.3	25.4
315	64.6	25.1	28.0	30.1	29.0	28.9
400	65.2	27.0	32.9	29.8	29.8	30.6
500	62.0	30.1	33.0	32.0	32.6	32.5
630	63.0	31.5	32.5	34.1	34.7	33.7
800	63.5	32.4	34.6	33.6	34.1	34.1
1000	67.7	34.4	36.1	34.3	34.9	35.0
1250	69.8	34.0	35.5	35.4	35.2	35.4
1600	69.6	33.3	34.7	33.0	33.4	33.6
2000	67.6	34.5	36.7	35.7	34.9	35.7
2500	65.6	40.9	42.8	41.3	41.3	41.7
3150	61.2	41.5	42.2	41.3	40.3	41.2
4000	57.1	39.3	39.2	39.1	38.2	38.8

Table C12. Noise Intrusion Reduction, Data Set No. 2, Test House No. 8

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	66.3	17.3	15.1	15.6	17.6	16.0
63	70.4	14.4	21.7	15.9	16.2	17.3
80	67.6	16.1	9.7	11.9	16.1	11.8
100	66.0	13.2	11.9	15.5	16.5	14.2
125	71.9	18.5	14.4	14.0	19.0	15.3
160	73.7	22.7	20.3	18.5	19.4	19.3
200	66.9	22.1	22.2	20.8	24.8	22.3
250	70.9	23.1	27.1	25.8	29.1	27.1
315	72.2	26.2	24.2	25.2	28.1	25.5
400	64.7	26.9	23.9	25.4	28.0	25.5
500	62.4	26.7	28.7	25.4	31.1	27.8
630	62.9	29.6	31.4	30.9	31.9	31.4
800	64.0	30.0	32.3	29.6	32.8	31.3
1000	68.3	29.6	31.9	31.2	33.4	32.1
1250	70.6	28.3	31.3	32.2	32.4	31.9
1600	71.2	28.3	30.3	30.9	32.1	31.0
2000	69.6	29.9	32.9	33.4	33.9	33.4
2500	67.0	34.6	35.2	33.2	36.1	34.7
3150	63.3	36.8	37.4	35.0	37.3	36.4
4000	58.7	31.9	32.8	31.9	31.3	32.0

Table C13. Noise Intrusion Reduction, Data Set No. 2, Test House No. 9, Passby No. 1

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	[illegible].1	12.6	14.1	12.1	18.1	14.1
63	6[illegible]	13.7	14.3	13.6	17.9	14.9
80	73.2	17.7	18.2	18.6	23.8	19.6
100	76.1	19.7	17.0	15.1	18.7	16.7
125	74.5	23.5	20.[illegible]	26.8	18.0	20.5
160	76.7	19.4	2[illegible].0	24.5	23.4	22.2
200	75.6	20.3	18.[illegible]	24.4	25.6	21.9
250	71.7	19.2	22.5	27.9	25.7	24.8
315	71.2	20.5	26.7	29.4	22.8	25.5
400	72.2	23.4	27.8	28.3	24.6	26.6
500	70.4	28.1	28.8	29.6	24.8	27.2
630	68.6	30.8	32.1	32.3	31.6	32.0
800	75.3	32.3	34.3	35.0	32.8	33.9
1000	80.5	33.8	35.8	35.8	33.5	34.8
1250	83.1	36.3	39.0	39.1	36.3	37.9
1600	84.3	37.1	40.3	41.4	40.3	40.6
2000	81.8	37.4	39.7	40.5	40.3	40.2
2500	78.4	36.1	38.0	36.9	39.8	38.1
3150	75.6	39.1	40.6	41.3	40.6	40.8
4000	70.5	37.2	40.3	41.7	4[illegible].7	40.9

Table C14. Noise Intrusion Reduction, Data Set No. 2, Test House No. 9, Passby No. 2

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	67.9	15.5	17.2	10.6	19.5	14.1
63	69.9	16.8	16.1	16.0	23.2	17.4
80	73.7	19.2	13.6	18.9	19.3	16.4
100	71.1	21.8	22.7	21.0	17.6	19.9
125	81.1	26.1	27.4	30.8	21.6	25.0
160	72.1	20.7	20.7	24.4	25.5	23.0
200	70.2	20.7	19.0	23.3	23.1	21.3
250	67.5	18.5	19.7	27.4	24.0	22.6
315	69.7	21.3	25.6	29.9	23.9	25 8
400	71.1	23.7	27.7	28.1	24.0	26.2
500	70.6	28.3	28.2	29.8	24.2	26.7
630	68.5	31.6	33.4	32.3	32.4	32.7
800	76.2	32.8	34.9	35.4	34.2	34.8
1000	80.7	32.2	34.6	34.0	33.6	34.0
1250	83.2	36.1	39.1	39.1	36.3	38.0
1600	84.0	37.4	40.0	41.7	39.6	40.3
2000	81.1	38.1	39.8	39.8	40.1	39.9
2500	78.1	36.7	37.4	36.8	39.3	37.7
3150	75.4	38.7	40.4	40.4	40.2	40.3
4000	70.9	38.2	40.7	42.2	40.2	41.0

Table C15. Noise Intrusion Reduction, Data Set No.2, Test House No.9, Passby No.3

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	68.5	14.4	15.9	8.6	15.9	12.0
63	71.3	17.3	15.5	15.2	22.2	16.7
80	75.9	20.3	14.2	20.6	20.0	17.2
100	70.3	20.5	15.6	17.4	19.9	17.3
125	81.1	24.1	26.1	27.3	22.6	24.9
160	76.3	18.9	22.5	24.2	23.6	23.4
200	71.9	22.2	17.8	22.5	23.5	20.5
250	69.8	19.5	20.7	26.5	25.0	23.3
315	70.3	21.6	25.8	29.6	22.8	25.2
400	71.7	25.0	27.7	29.4	24.7	26.8
500	70.6	28.3	29.1	29.8	25.2	27.5
630	68.2	30.4	31.6	30.4	31.5	31.1
800	76.0	32.6	34.6	35.5	33.3	34.4
1000	80.5	33.2	35.3	34.4	33.0	34.1
1250	83.2	36.5	38.7	37.6	36.2	37.4
1600	83.6	37.6	40.0	41.8	39.9	40.5
2000	81.6	37.4	39.4	39.7	40.1	39.7
2500	78.3	36.0	37.5	36.5	39.1	37.6
3150	75.7	38.8	40.8	41.1	40.3	40.7
4000	70.8	36.7	40.4	41.6	39.8	40.5

Table C16. Noise Intrusion Reduction, Data Set No.2, Test House No.9, Passby No.4

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	67.0	15.5	16.2	9.8	16.9	13.0
63	66.0	13.7	11.3	12.8	18.4	13.3
80	76.4	20.5	14.7	19.5	20.2	17.4
100	83.4	22.0	22.9	24.8	19.2	21.7
125	87.3	26.8	29.6	30.7	20.3	24.2
160	73.3	19.5	22.3	23.4	25.9	23.6
200	73.1	20.8	17.8	23.1	24.6	20.8
250	70.3	19.8	20.4	27.7	25.2	23.4
315	72.2	21.8	27.4	31.0	24.0	26.6
400	71.7	24.7	27.6	29.7	24.7	26.8
500	71.4	27.8	27.5	30.0	24.9	27.0
630	68.0	31.1	32.4	31.7	31.9	32.0
800	74.0	32.4	34.5	35.1	31.8	33.6
1000	81.1	32.9	35.4	35.2	33.0	34.4
1250	83.7	36.9	38.9	38.5	36.4	37.8
1600	84.1	38.0	40.2	41.3	39.1	40.1
2000	82.1	38.0	39.9	40.3	40.7	40.3
2500	79.0	36.6	37.5	36.0	39.3	37.4
3150	76.3	39.0	40.8	41.0	41.0	40.9
4000	71.7	38.6	40.9	42.2	41.0	41.3

Table C17. Noise Intrusion Reduction, Data Set No.2, Test House No.9, Passby no.5

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	67.8	13.4	15.3	9.7	16.8	12.8
63	69.2	17.7	16.5	15.3	22.2	17.1
80	74.8	18.6	15.2	19.2	21.4	17.8
100	70.8	19.7	16.7	18.0	19.1	17.8
125	77.3	22.4	22.2	27.0	20.3	22.4
160	77.6	20.3	22.2	25.5	25.2	24.0
200	71.5	21.5	17.3	22.4	22.8	20.1
250	70.5	20.6	20.9	25.7	23.7	23.0
315	70.1	21.7	26.4	29.9	23.6	25.9
400	71.4	22.7	27.9	28.1	24.2	26.3
500	70.9	27.9	28.2	30.3	23.9	26.6
630	68.1	31.0	32.1	30.6	32.1	31.5
800	74.0	31.9	33.6	35.3	31.4	33.1
1000	80.1	34.1	34.9	34.7	34.1	34.6
1250	83.2	36.5	38.6	38.5	36.6	37.8
1600	83.5	37.7	40.0	41.3	39.1	40.0
2000	81.3	37.3	39.8	39.7	40.3	39.9
2500	78.1	36.7	36.8	36.3	39.3	37.3
3150	75.1	38.6	40.3	40.3	40.3	40.3
4000	70.5	37.2	40.0	41.7	39.8	40.4

Table C18. Noise Intrusion Reduction, Data Set No.2, Test House No.9
Door Open

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	71.3	8.2	7.6	5.5	10.7	7.4
63	68.6	8.2	9.0	7.6	12.1	9.2
80	71.2	9.6	13.7	11.9	17.7	13.8
100	76.6	13.3	15.1	9.7	14.3	12.3
125	77.9	10.5	19.2	10.4	13.4	13.0
160	78.3	8.0	19.0	8.3	18.6	12.4
200	76.4	13.7	13.6	18.4	17.8	16.0
250	71.1	17.2	15.8	17.9	19.3	17.4
315	70.8	19.0	16.4	16.3	19.8	17.2
400	71.5	18.1	17.6	14.8	17.5	16.4
500	70.7	19.2	16.1	16.3	18.3	16.8
630	68.1	15.0	15.5	13.3	17.4	15.1
800	74.8	16.2	16.7	12.9	18.7	15.4
1000	80.3	17.2	15.9	13.7	18.0	15.5
1250	82.9	16.2	16.2	13.0	19.1	15.4
1600	82.4	13.4	14.7	11.8	17.4	14.0
200	81.0	15.1	15.0	11.9	17.7	14.2
2500	78.0	14.8	15.0	12.3	16.5	14.2
3150	75.2	15.9	16.3	15.0	18.1	16.3
4000	70.7	15.6	17.1	15.4	18.3	16.8

Table C19. Summary of Spatial Average Noise Intrusion Reduction Values for all Nine Test Houses - Data Set No.2

Band Center Freq., Hz	Average Noise Intrusion Reductions, dB										
	Test House No.1	Test House No.2	Test House No.3	Test House No.4	Test House No.5	Test House No.6	Test House No.7	Test House No.8	Test House No.9	Avg. All Houses	Octave Band Avg. All Houses
50	13.4	16.0	12.5	11.5	11.6	13.7	14.5	16.0	14.1	13.4	
63	14.9	14.5	22.6	15.0	12.5	18.0	14.6	17.3	14.9	15.3	15.0
80	19.2	19.2	26.0	20.0	16.6	17.2	18.2	11.8	19.6	17.2	
100	23.1	23.6	26.2	18.9	15.0	17.8	17.7	14.2	16.7	17.8	
125	27.5	28.3	24.8	21.4	16.5	20.0	21.5	15.3	20.5	19.9	19.4
160	20.0	23.6	24.4	23.8	17.3	21.4	24.4	19.3	22.2	21.1	
200	23.9	26.7	27.0	25.0	23.7	23.9	29.2	22.3	21.9	24.3	
250	29.3	26.0	33.5	29.3	28.9	24.7	25.4	27.1	24.8	27.0	25.9
315	28.1	24.6	30.7	28.1	29.3	24.8	28.9	25.5	25.5	26.8	
400	26.9	25.3	29.3	31.1	29.4	25.9	30.6	25.5	26.6	27.4	
500	30.7	26.8	30.9	30.1	30.6	22.8	32.5	27.8	27.2	27.8	28.3
630	31.1	29.2	30.3	33.6	32.8	25.7	33.7	31.4	32.0	30.3	
800	32.6	32.4	31.6	35.6	36.7	30.6	34.1	31.3	33.9	32.8	
1000	32.0	35.4	34.1	38.2	38.3	31.6	35.0	32.1	34.8	34.0	33.7
1250	32.4	36.0	35.9	39.3	36.7	32.2	35.4	31.9	37.9	34.6	
1600	34.0	36.5	39.0	40.3	37.8	34.8	33.6	31.0	40.6	35.3	
2000	35.1	35.8	34.0	36.7	36.1	30.7	35.7	33.4	40.2	34.6	35.5
2500	34.7	36.1	36.6	38.4	38.6	37.4	41.7	34.7	38.1	36.9	
3150	33.7	33.8	38.1	39.6	39.0	37.4	41.2	36.4	40.8	37.0	
4000	32.3	37.4	39.1	38.1	39.8	34.8	38.8	32.0	40.9	35.9	36.2

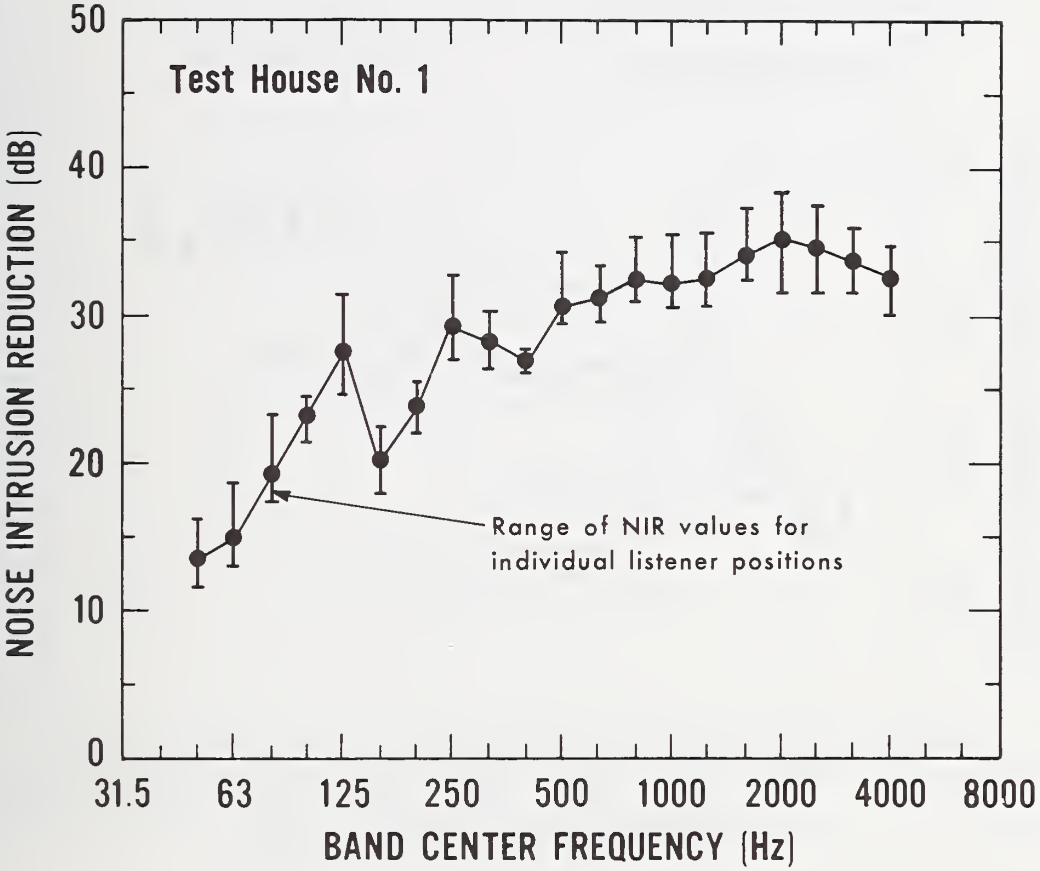

Figure C1. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 1, Data Set No. 2.

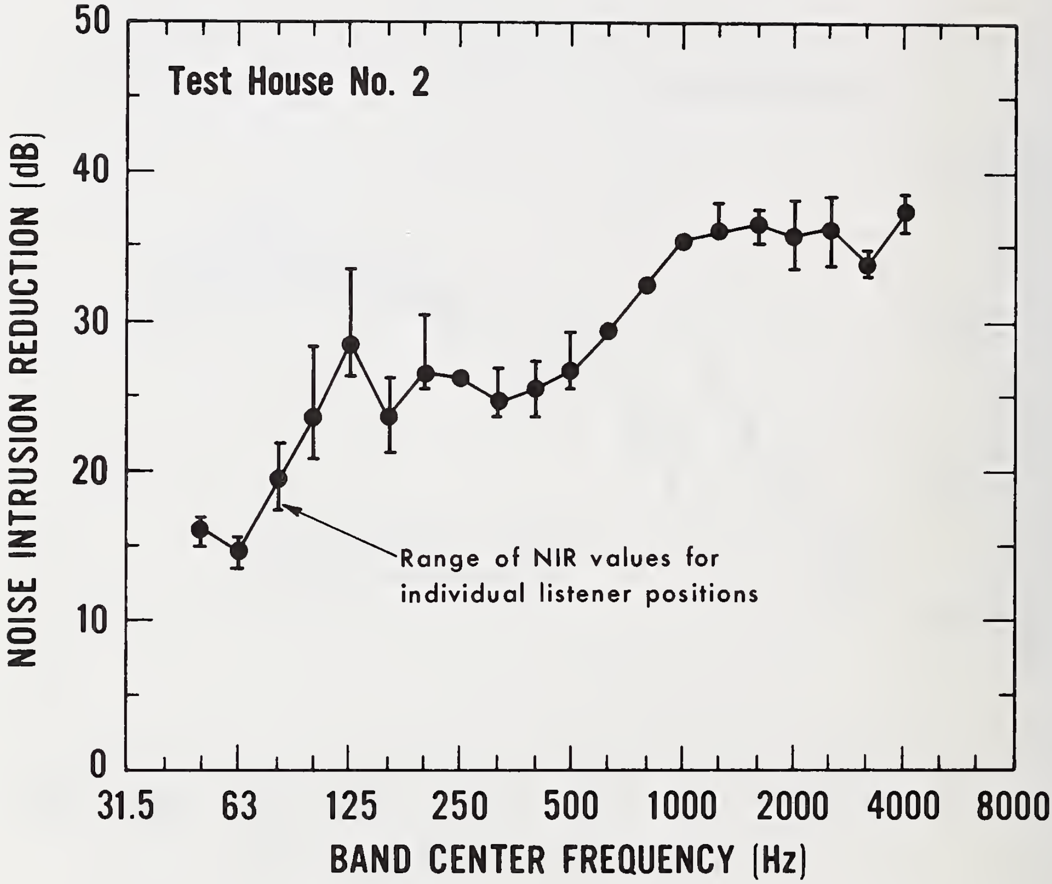

Figure C2. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 2, Data Set No. 2.

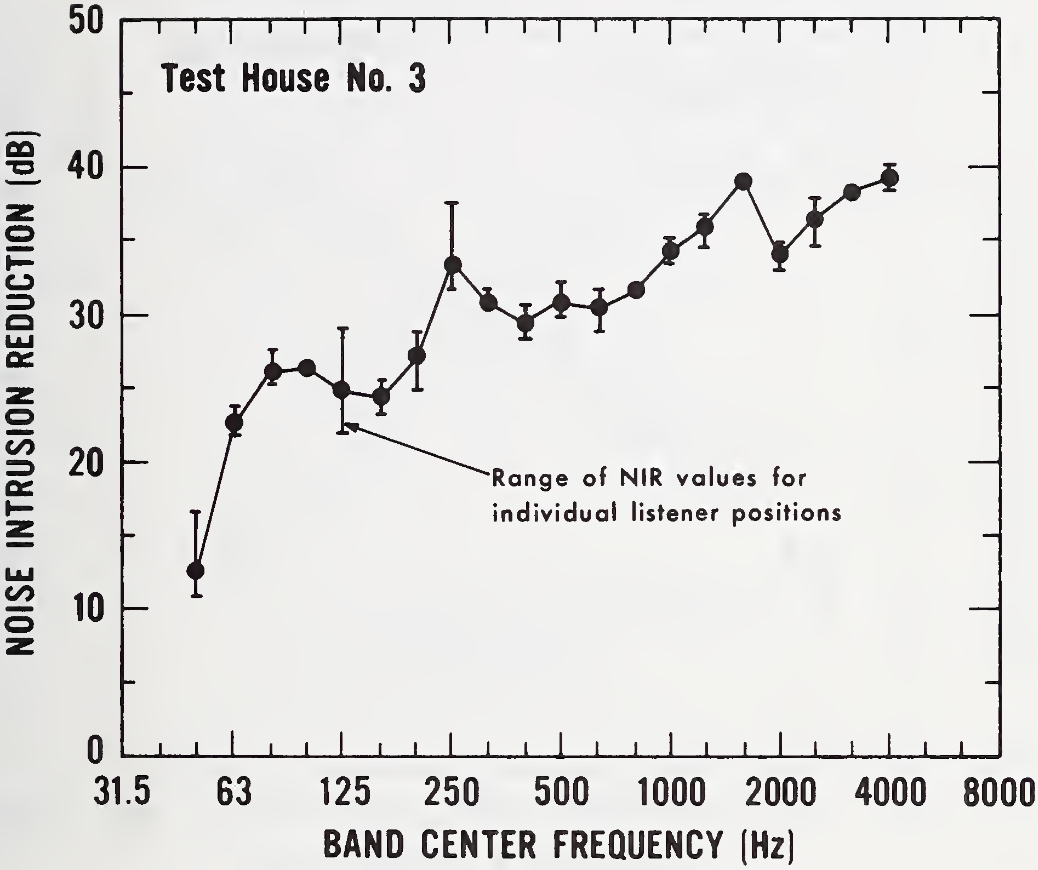

Figure C3. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 3, Data Set No. 2.

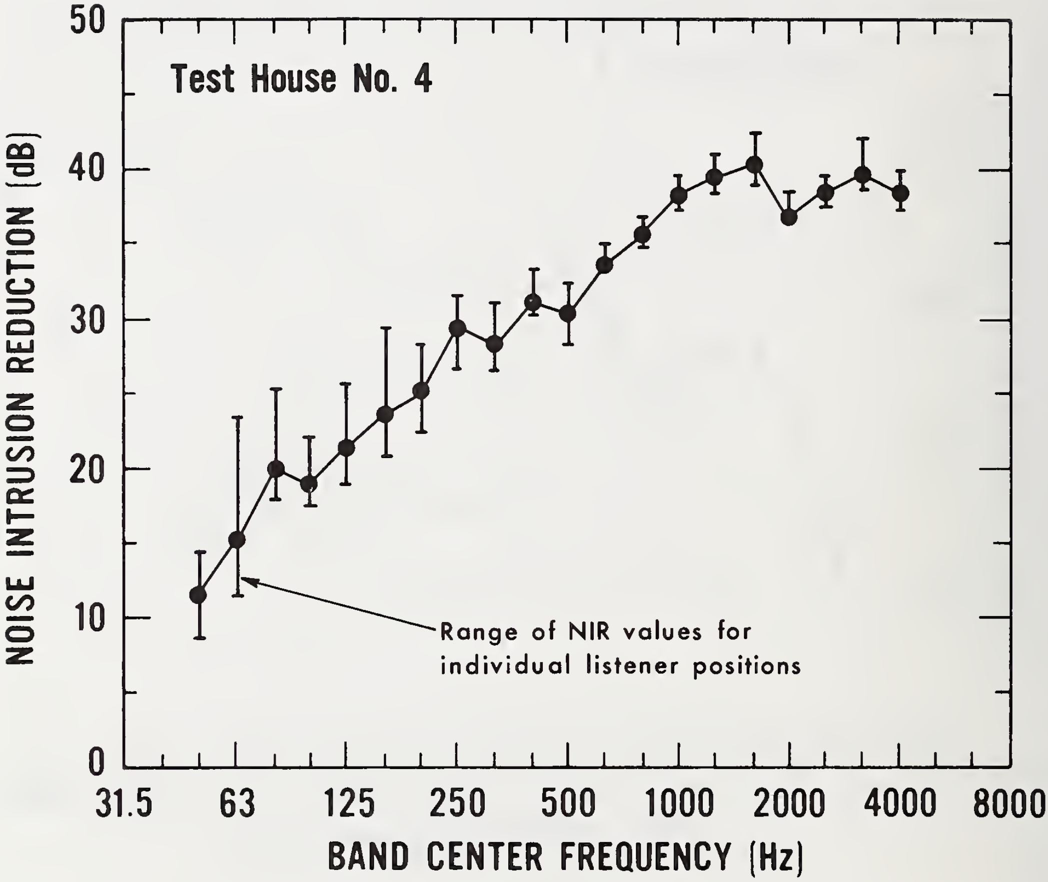

Figure C4. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 4, Data Set No. 2.

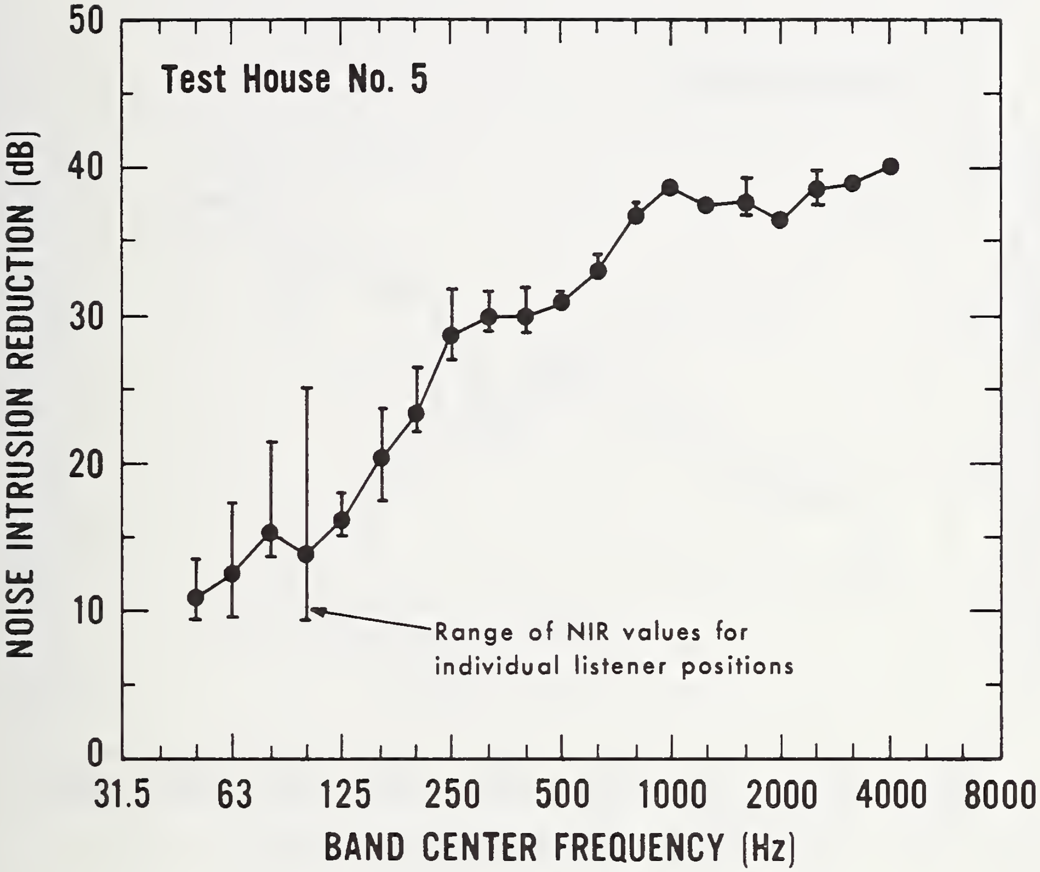

Figure C5. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 5, Data Set No. 2.

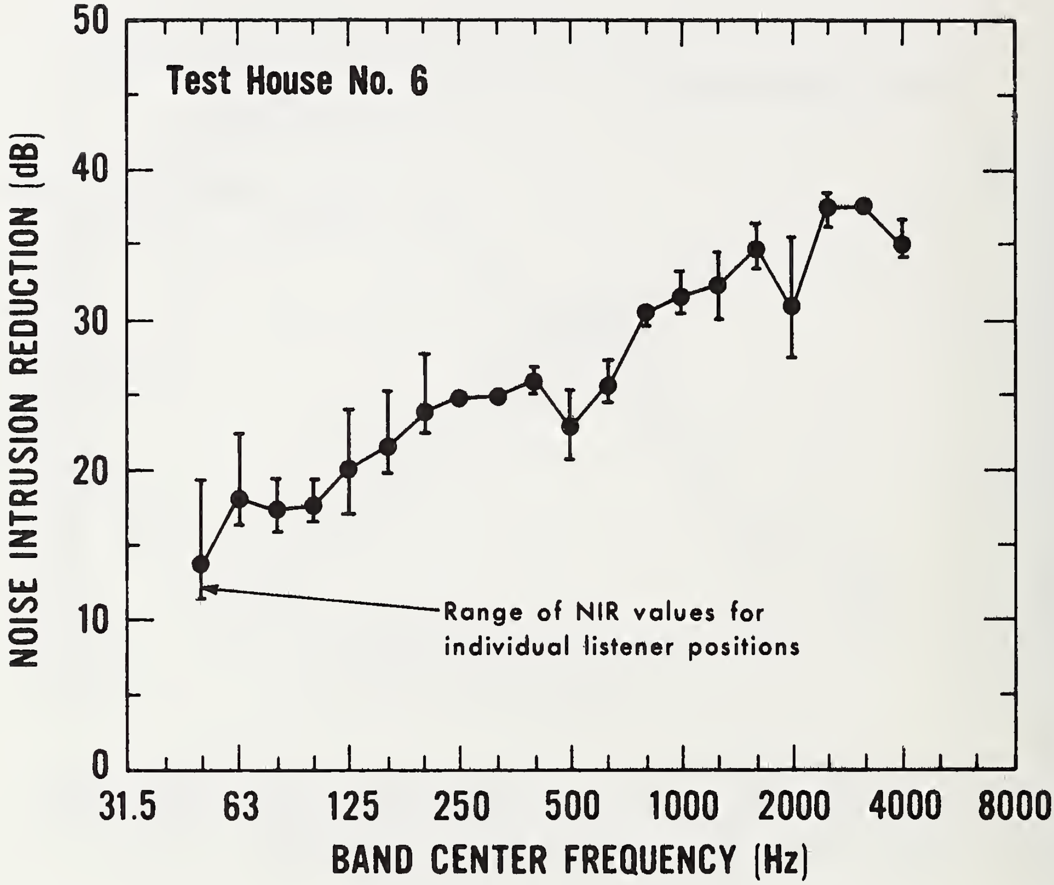

Figure C6. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 6, Data Set No. 2.

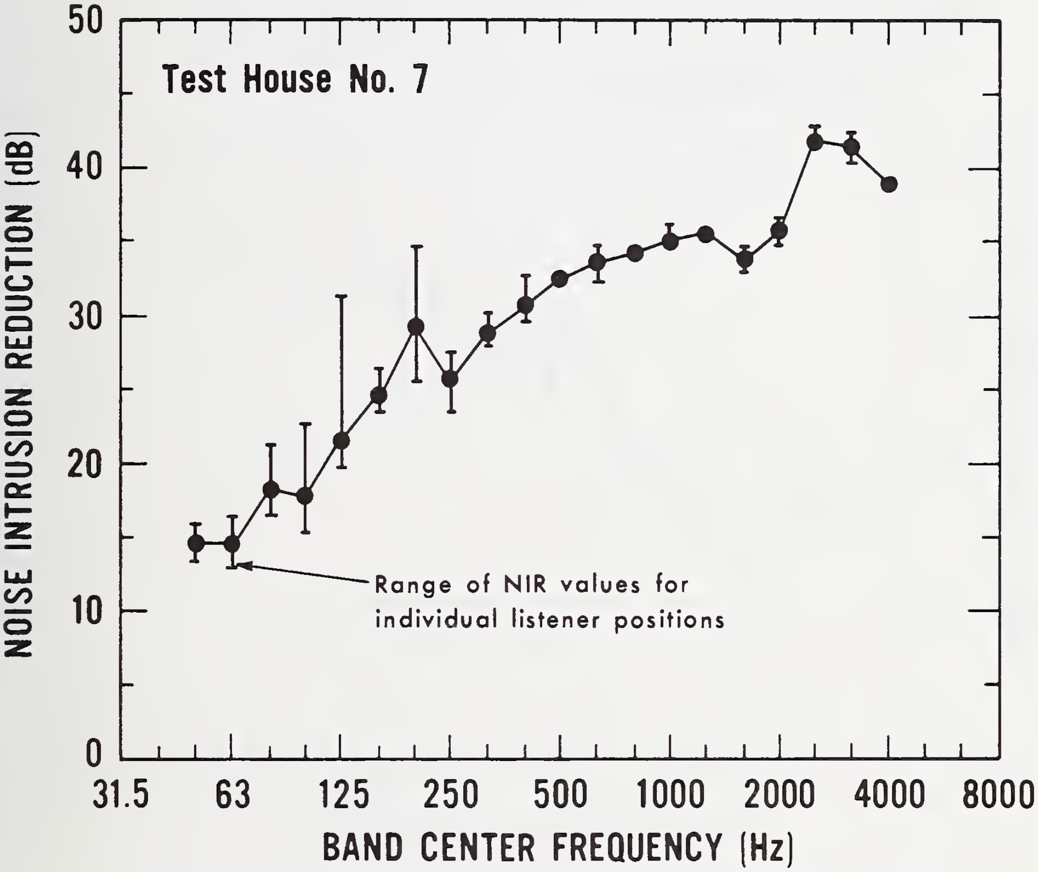

Figure C7. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 7, Data Set No. 2.

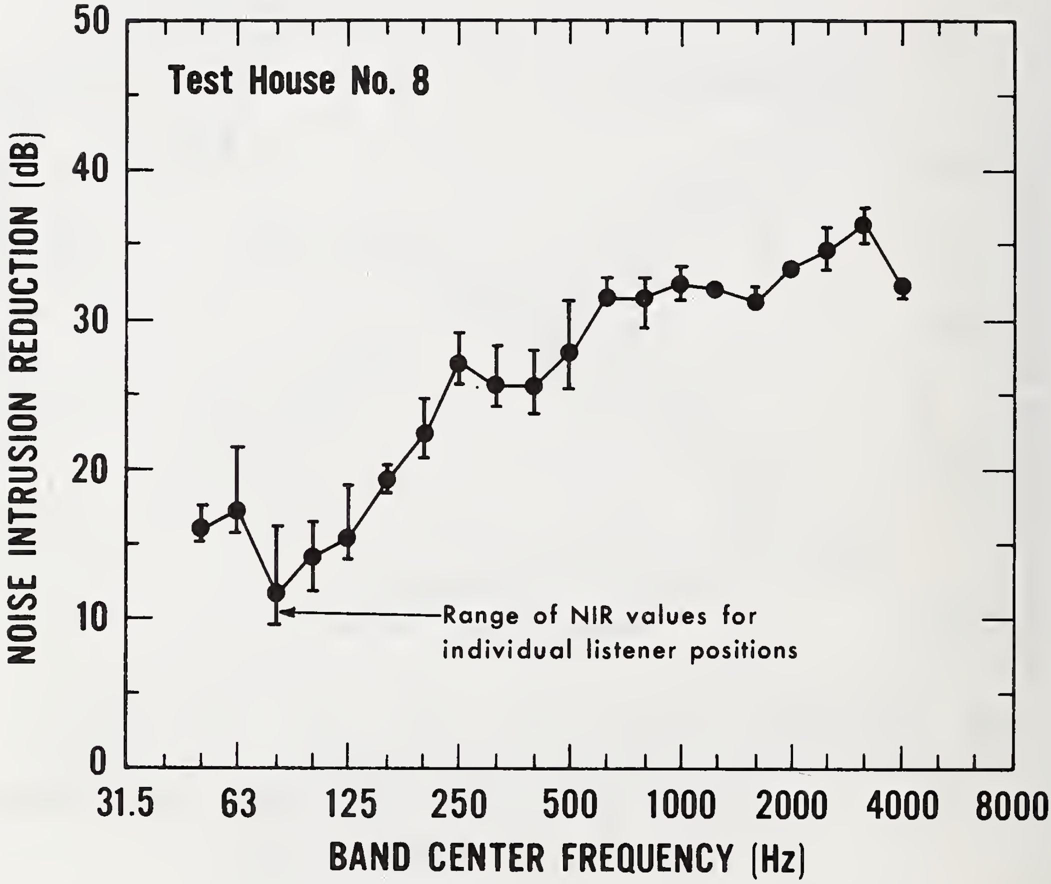

Figure C8. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 8, Data Set No. 2.

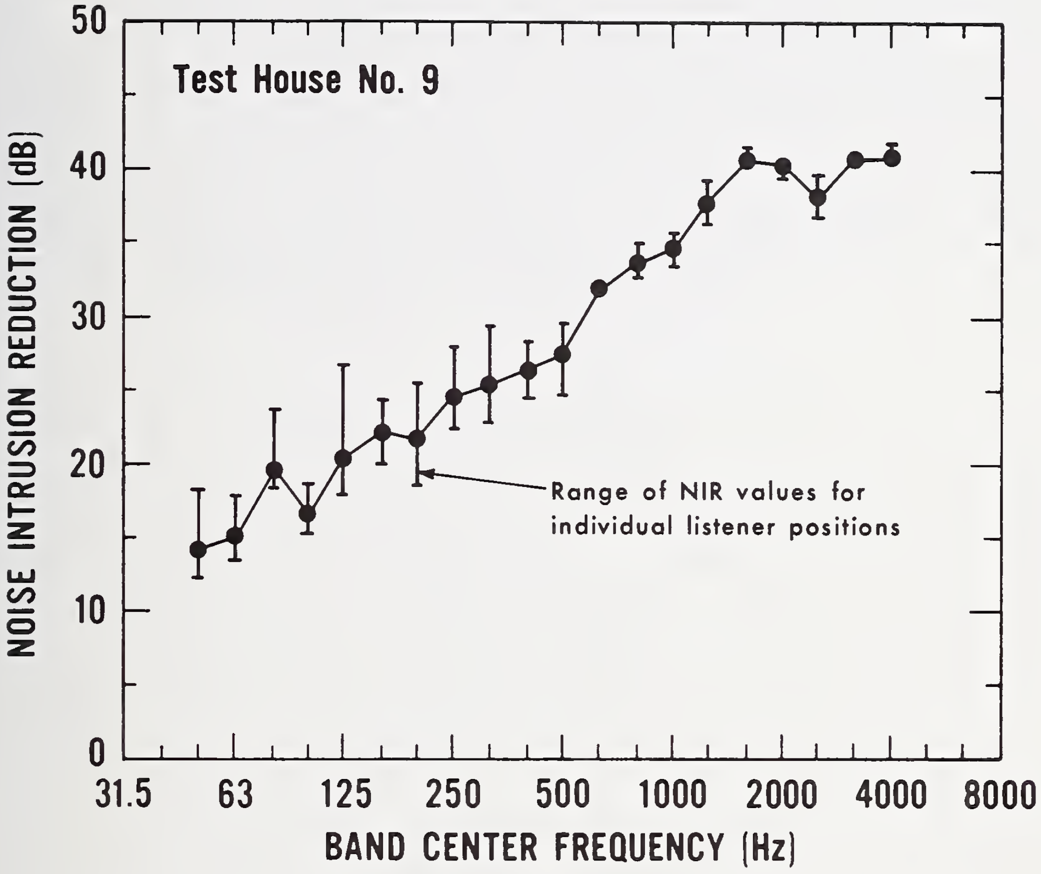

Figure C9. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 9, Data Set No. 2.

Appendix D. Values of Noise Intrusion Reduction Determined from Outdoor and Indoor 1/3-Octave Band Sound Exposure Levels

The NIR values presented in this Appendix were obtained from 1/3-octave band sound exposure levels (SEL) as determined at each exterior and interior microphone position and correspond to Data Set No. 3 of Section 3.3. The values of NIR from 50 to 4000 Hz obtained using this data reduction technique are presented in Tables D1 and D2 for Test Houses No. 6 and No. 8, respectively. In each table, the average SEL values for the two 3-m microphone positions are presented along with the NIR values for the interior reference microphone position, the values for the three individual listener microphone positions, and the average over the listener positions, as determined using Eq. (4) of Section 4.1.1. The average NIR values determined for the listener positions at the two test houses are plotted in Figures D1 and D2.

Table D1. Noise Intrusion Reduction, Data Set No.3, Test House No.6

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	60.0	10.6	11.2	17.8	9.9	11.9
63	61.4	17.7	15.7	20.8	15.7	16.8
80	67.9	15.5	18.0	13.8	19.3	16.4
100	63.7	15.4	18.2	14.9	18.7	16.9
125	70.5	21.1	22.4	18.6	23.7	21.0
160	68.1	22.2	19.4	20.8	24.9	21.1
200	65.4	20.5	23.0	21.9	26.2	23.3
250	60.2	20.4	22.2	24.2	23.6	23.3
315	60.0	19.9	23.6	24.9	23.3	23.9
400	56.7	23.8	24.4	26.3	25.8	25.4
500	55.0	24.6	22.7	25.7	27.4	24.8
630	53.6	27.7	25.9	27.7	29.4	27.4
800	54.9	28.0	28.3	29.9	30.4	29.4
1000	58.1	29.7	30.4	30.4	32.2	30.9
1250	60.9	30.4	32.8	30.5	33.1	32.0
1600	62.2	32.5	34.4	33.3	34.7	34.1
2000	61.6	31.7	33.3	28.1	34.1	31.0
2500	61.0	32.9	35.6	34.2	35.3	35.0
3150	58.0	30.1	34.7	34.9	34.9	34.8

Table D2. Noise Intrusion Reduction, Data Set No.3, Test House No.8

1/3-Octave Band Center Frequency, Hz	Average Exterior Level, dB	NIR, dB				
		Interior Reference Position	Listener Position No.1	Listener Position No.2	Listener Position No.3	Average of Listener Positions
50	61.2	16.4	16.3	14.2	16.8	15.6
63	65.5	10.0	21.2	16.1	16.7	17.5
80	64.0	17.1	8.8	12.2	16.3	11.4
100	63.3	18.0	12.3	15.9	18.9	14.9
125	69.4	19.3	16.3	17.2	20.0	17.6
160	69.6	21.3	20.1	19.9	21.6	20.5
200	63.4	21.6	22.0	22.3	26.0	23.1
250	66.6	22.4	25.4	25.4	27.9	26.1
315	67.9	25.8	25.3	25.9	28.6	26.4
400	59.8	26.4	25.6	27.0	28.2	26.8
500	58.3	27.1	28.3	26.9	30.2	28.3
630	58.6	29.6	30.9	30.8	32.1	31.2
800	60.1	30.1	32.3	31.4	33.0	32.2
1000	63.7	28.9	31.8	31.1	32.8	31.8
1250	65.2	28.1	31.5	31.7	32.0	31.7
1600	65.4	28.0	30.1	30.8	32.2	30.9
2000	63.4	28.7	31.5	32.5	33.2	32.3
2500	61.1	33.0	33.9	32.6	34.7	33.6
3150	58.1	34.7	35.5	34.0	35.1	34.8

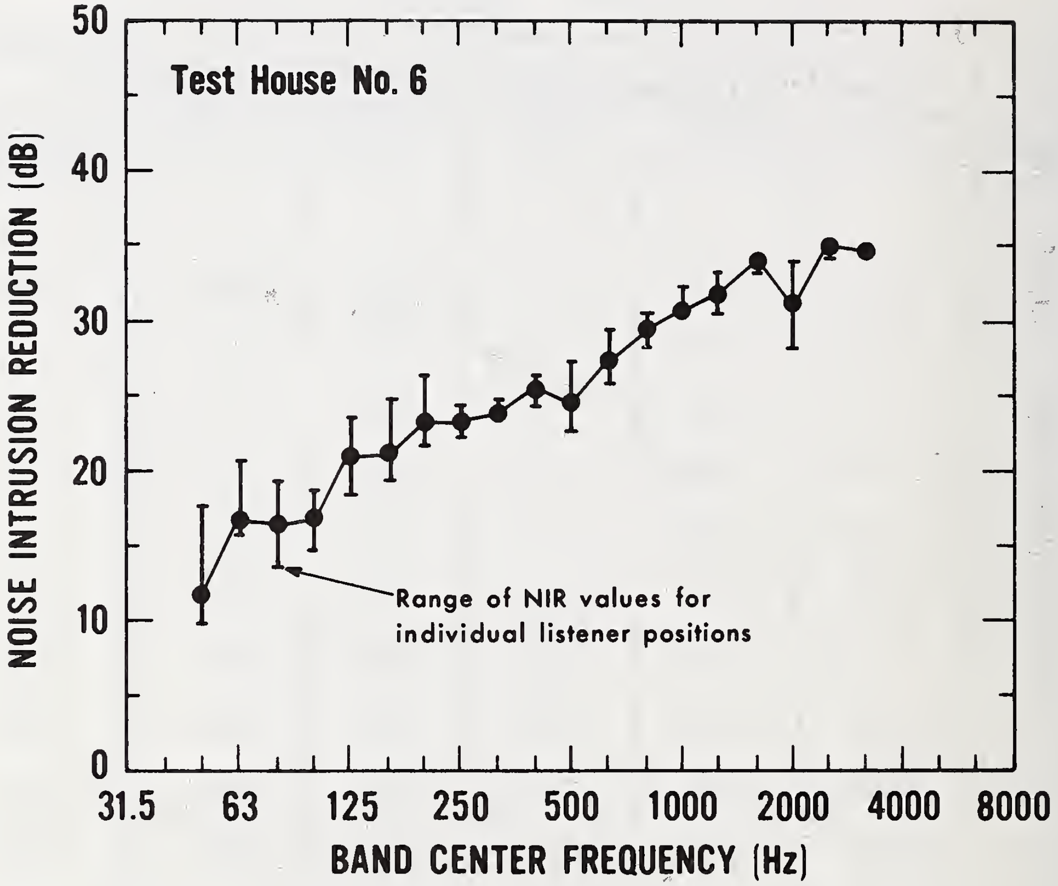

Figure D1. Noise Intrusion Reduction (average and range over listener positions) for Test House No. 6, Data Set No. 3.

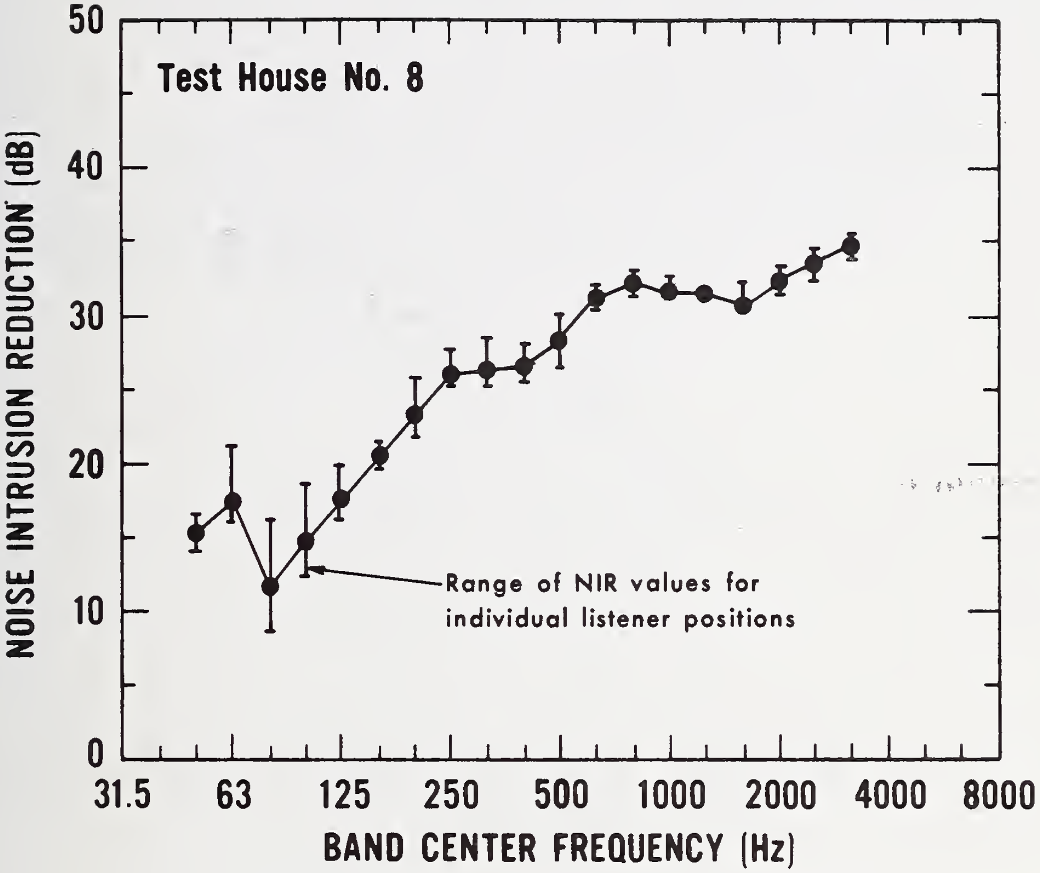

Figure D2. Noise Intrusion Reduction (average and range over listener positions) for Test House NO. 8, Data Set No. 3.

Appendix E. Electronic Filter Simulating Average Noise Intrusion Reduction

For psychoacoustic tests to be carried out as part of this overall study of highway noise criteria, it is desired to have an electronic filter that will modify the signal from recordings of outdoor traffic noise so as to yield a signal that corresponds closely to the signal that would be expected inside a typical house. For this purpose it was decided to design a filter that would have a frequency response simulating the average Noise Intrusion Reduction for the nine houses included in the present investigation over the frequency range from 50 to 4,000 Hz and that would have a nominally flat frequency response above and below these frequencies. In order to attain the desired performance, an active filter circuit as shown in Fig. E1 was selected. The transfer function of this circuit is:

$$H(\omega) = A_o \frac{1+j\alpha\omega\tau}{1+j\omega\tau}, \tag{E.1}$$

where

$$A_o = \frac{R_c + R_f}{R_i}$$

$$\tau = R_c C_f$$

$$\alpha = \frac{R_f}{R_f + R_c}$$

$$j = \sqrt{-1}$$

$$\omega = 2\pi f = \text{circular frequency}$$

and R_i, R_c, R_f, and C_f are circuit elements as shown in Fig. E1. The amplitude density spectrum of this filter is

$$S(\omega) = |H(\omega)|^2 = A_o^2 \frac{1 + \alpha^2\omega^2\tau^2}{1 + \omega^2\tau^2}. \tag{E.2}$$

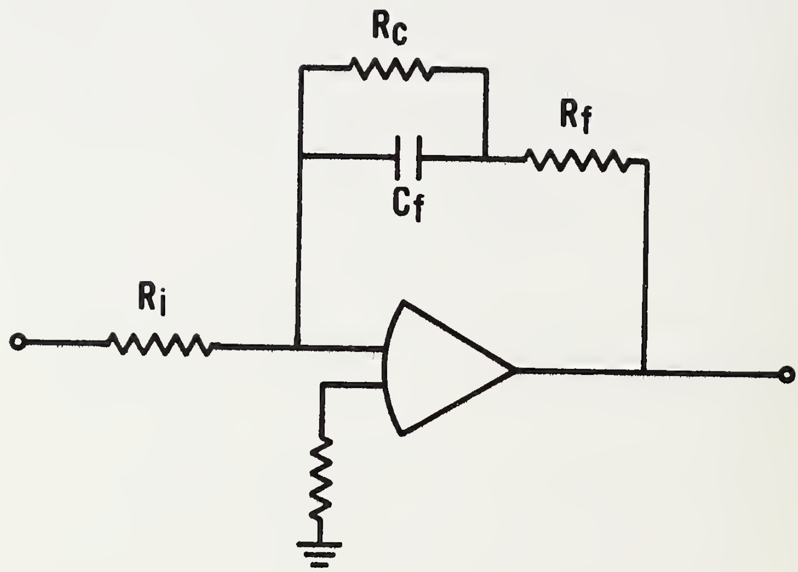

Figure E1. Circuit diagram for active filter used to simulate average Noise Intrusion Reduction.

Values of α, τ, and A_o were selected so as to minimize the mean-square deviation between $-10 \log [S(\omega)]$ and the octave-band Noise Intrusion Reduction values averaged over the nine houses (i.e., the values in column 11 of Table C19 of Appendix C). The values so obtained are:

$$\alpha = 0.0526$$
$$\tau = 0.00302$$
$$A_o \quad 0.279$$

The smooth curve in Fig. E2 shows the values of $-10 \log [S(\omega)]$ computed from Eq. (E.2) using these values of α, τ, and A_o. The triangular symbols represent the average octave-band Noise Intrusion Reduction values (column 11 of Table C19) that were used to generate the values of the parameters for the electronic filter. The deviations of these octave band Noise Intrusion Reduction values from the smooth curve are less than ± 0.3 dB except at 250 and 500 Hz where the deviations are +1.4 and -1.4 dB, respectively. The root-mean-square deviation of the seven octave-band values from the smooth curve is 0.8 dB.

The circular symbols in Fig. E2 represent the 1/3-octave band data for the average of the nine houses (column 10 in Table C19). The deviations from the smooth curve are less than ± 1.0 dB except at 200, 250, 500, and 2000 Hz, where the deviations are +1.5, +2.5, -1.9, and -1.1 dB, respectively. The root-mean-square deviation of the twenty-one 1/3-octave band values from the smooth curve is 0.9 dB.

In addition to the filter described above that was fitted to the data obtained as part of the present investigation, Eq. (E.2) was fitted to the average outdoor-to-indoor octave-band noise isolation data shown as the last row of Table E1 in order to obtain the filter parameters for a "warm climate" filter. The following filter parameters were selected:

$$\alpha = 0.3043$$
$$\tau = 0.000749$$
$$A_o = 0.1445$$

The solid smooth curve in Fig. E3 shows the values of $-10 \log [S(\omega)]$ computed from Eq. (E.2) using these values of α, τ, and A_o. The triangular symbols represent the averaged experimental values listed at the bottom of Table E1, while the upper and lower limits indicate the range of the values listed in Table E1. The dashed curve corresponds to the filter response curve for Washington, DC, area houses as shown in Fig. E2.

Values of the two filter response curves are listed in Table E2, for 1/3-octave band frequencies from 10 to 20,000 Hz.

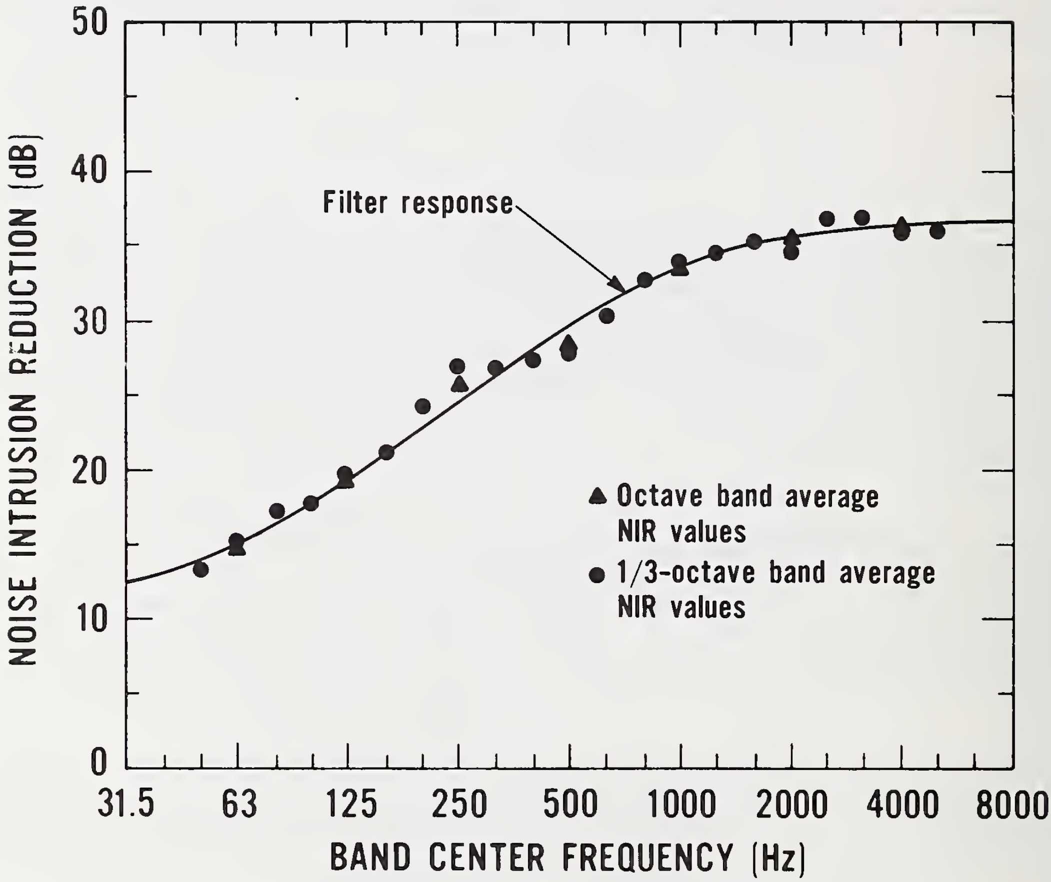

Figure E2. Average Noise Intrusion Reduction values, for houses in the Washington, D.C., area, compared to computed response of an electronic filter having the circuit of Fig. E1 and circuit parameter values of α= 0.0526, τ= 0.00302, and A_o = 0.279.

Table E1. Outdoor-to-indoor noise isolation, in decibels, for houses in "warm climates." The average values shown in the last row were averaged using Eq. (7), with the data for each city being weighted in proportion to the number of rooms for which measurements were made.

City	No. of Houses	No. of Rooms	Frequency, Hz						
			63	125	250	500	1000	2000	4000
Miami[a]	4	8	18.0	17.0	18.0	22.5	25.0	27.0	29.0
Los Angeles, CA[a]	2	4	19.0	16.0	20.0	21.5	25.0	25.0	26.5
Wallops Island, VA[a]									
Brick Construction	1	4	17.1	23.0	21.0	20.0	27.8	30.3	30.5
Wood Construction	1	4	16.3	21.1	21.3	20.3	21.3	24.0	25.0
Playa Del Rey, CA[a]	1	3	16.9	14.5	21.0	22.5	23.5	24.8	28.8
Westchester, CA[a]	1	5	16.7	17.3	23.8	25.4	28.2	29.4	32.4
Los Angeles, CA[a]	11	11	16.0	20.0	21.0	24.0	25.0	26.0	28.0
AVERAGE			16.7	18.4	20.3	22.9	24.8	26.1	28.1

[a] House Noise-Reduction Measurements for Use in Studies of Aircraft Flyover Noise, SAE Aerospace Information Report 1081 (1971).

[b] Noise Environment of Urban and Suburban Areas (Federal Housing Administration, Department of Housing and Urban Development, Washington, DC, 1967).

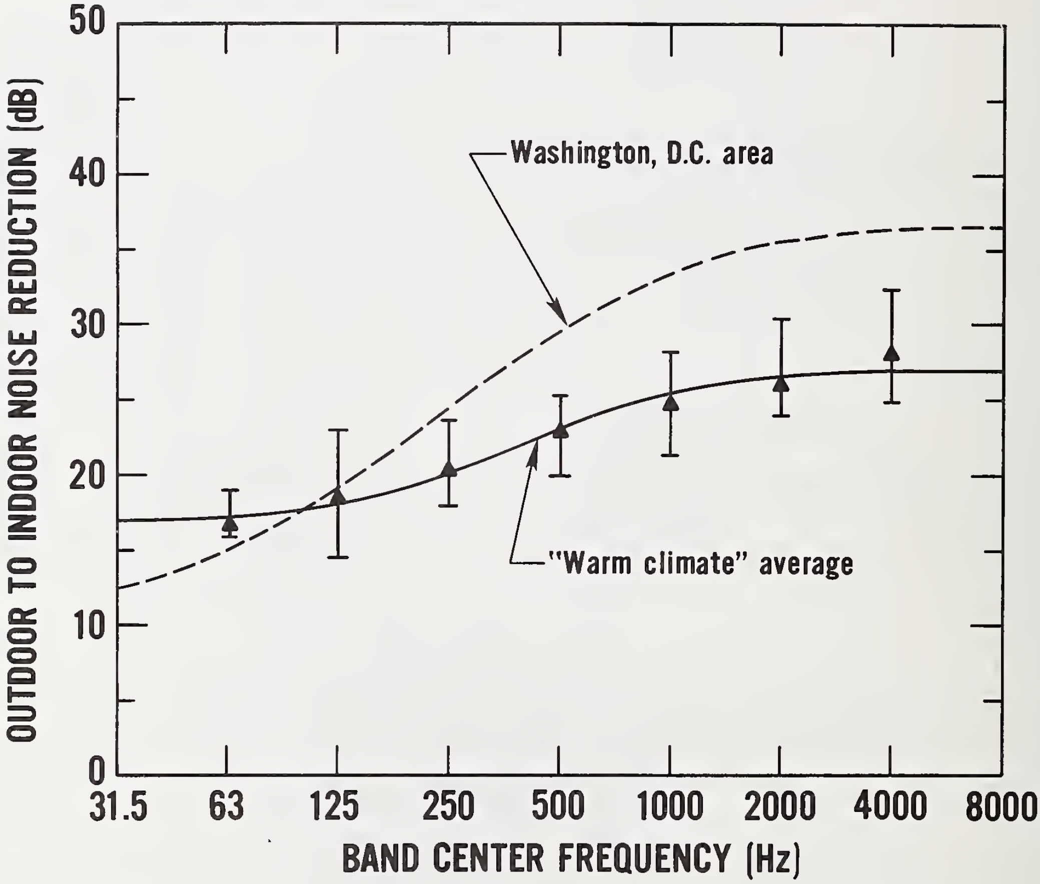

Figure E3. The solid curve corresponds to the computed response of a "warm climate" filter having the circuit of Fig. E2 and circuit parameter values of $\alpha = 0.3043$, $\tau = 0.000749$, and $A_o = 0.1445$. The symbols are described in the text. The dashed curve corresponds to the computed filter response from Fig. E2.

Table E2. Tabulated values for smoothed filter response corresponding to Washington, DC, area houses and to "warm climate" houses.

Frequency (Hz)	Filter Response (dB)	
	Washington, DC	"Warm Climate"
10	11.3	16.8
12.5	11.3	16.8
16	11.5	16.8
20	11.7	16.8
25	12.0	16.9
31.5	12.4	16.9
40	13.1	16.9
50	13.9	17.0
63	14.9	17.1
80	16.3	17.3
100	17.7	17.6
125	19.2	18.0
160	21.1	18.5
200	22.8	19.2
250	24.5	20.1
315	26.3	21.0
400	28.1	22.1
500	29.7	23.2
630	31.2	24.1
800	32.6	25.0
1000	33.7	25.6
1250	34.5	26.1
1600	35.2	26.5
2000	35.7	26.7
2500	36.0	26.8
3150	36.3	26.9
4000	36.4	27.0
5000	36.5	27.1
6300	36.6	27.1
8000	36.6	27.1
10,000	36.6	27.1
12,500	36.6	27.1
16,000	36.6	27.1
20,000	36.6	27.1

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	NBS TN 1113-2		

4. TITLE AND SUBTITLE

Highway Noise Criteria Study: Outdoor/Indoor Noise Isolation

5. Publication Date

August 1980

6. Performing Organization Code

7. AUTHOR(S)

Paul R. Donavan, Daniel R. Flynn, and Simone L. Yaniv

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

6-3-0154

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

U. S. Department of Transportation
Federal Highway Administration
Office of Research, Environmental Design and Control
Washington, DC 20590

13. Type of Report & Period Covered

Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report documents a series of measurements of the outdoor-to-indoor noise isolation provided by nine houses in the Washington, DC, area. These measurements were carried out as part of a large research program developed to identify and quantify the important physical parameters which affect human response to time-varying traffic noise and to investigate various procedures for rating such noise so as to enable reliable predictions of subjective response to the noise. While a small truck was driven past each test house, simultaneous recordings were made of the sound level at three outdoor microphones and at four indoor microphones (three of which were positioned at representative listener positions). These recordings were analyzed to yield one-third octave band sound levels as functions of time and from these levels outdoor-to-indoor level differences were computed. Analyses are given of the influence of different experimental variables. It is found that microphone placement, both indoors and outdoors, is the major source of measurement uncertainty. The data from this study are in good agreement with sound isolation data reported in the literature for houses in colder climates.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acoustics; building acoustics; environmental pollution; noise control; noise isolation; sound

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